TECHNICAL REPORT

Demonstration of the MPV at Former Waikoloa Maneuver Area in Hawaii

ESTCP Project MR-201228

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14. ABSTRACT
The Man-Portable Vector (MPV) sensor was demonstrated at a live site at the Former Waikoloa Maneuver Area on Hawaii in January 2014 as part of the ESTCP Live-Site Program for Munitions Response. The MPV is an electromagnetic induction (EMI) sensor designed for munitions detection and classification. Its handheld form factor provides enhanced portability and ruggedness relative to vehicular-based systems. The Waikoloa site brought new challenges with the occurrence of multiple rocky outcrops that precluded use of vehicular-based systems, and soils with high magnetic remanent magnetization that caused sufficient geologic background noise to hide the response of buried objects. The study focused on a 1.5-acre parcel where targets of interest included 37 mm projectiles, 60 mm and 81 mm mortars. The MPV was first utilized for a detection survey after which 450 anomalies were selected for cued interrogation in standard cued mode. The detection survey was generally successful at covering the entire site and detecting potential targets. Classification of the cued data resulted in all UXO being correctly identified with 81% clutter rejection.

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ACRONYMS

AHRS	Attitude and Heading Reference System
BTG	Black Tusk Geophysics, Inc.
BUD	Berkeley UXO Discriminator
CFR	Code of Federal Regulations
cm	Centimeter
CRREL	Cold Regions Research and Engineering Laboratory (ERDC)
DAQ	Data Acquisition System
DGM	Digital Geophysical Mapping
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
HI	Hawaii
HASP	Health and Safety Plan
IDA	Institute for Defense Analyses
IVS	Instrument Verification Strip
m	Meter
mm	Millimeter
MPV	Man Portable Vector
msec	Millisecond
MR	Munitions Response
NH	New Hampshire
PI	Principal Investigator
POC	Points of Contact
RTK	Real-time Kinematic
sec	Second
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SVM	Support Vector Machine
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
UXO	Unexploded Ordnance

ACKNOWLEDGEMENTS

The MPV demonstration at Waikoloa was funded under the Environmental Security Technology Certification Program, project MR-201228. The project is based on technology that was funded at an earlier stage under the ESTCP projects MR-201158 and MR-201005. The MPV technology was pioneered by Kevin O'Neil and Benjamin Barrowes from the Engineering Research and Development Center (ERDC) at the Cold Regions Research and Engineering Laboratory (CRREL) in Dartmouth, New Hampshire and funding from the Strategic Environmental Research and Development Program (SERDP) project MM-1443. All generations of the MPV have been based on the EMI sensor technologies developed by David George of G&G Sciences, who has been fabricating and maintaining all MPVs.

The Waikoloa demonstration is a team effort that involved multiple parties. David George helped with initial testing on site to ensure that the technology was operational. The technology had been improved since the previous demonstration with the option to use additional transmitter coils to interrogate an anomaly with a single sounding and the capability to invert the data in near real-time and predict the buried target location. The demonstration also benefitted from the involvement of John Jackson from the Sacramento USACE, who participated in the entire data collection process. Experienced field crews, safety and logistical support were provided by Environet, a local company from Hawaii with first-hand knowledge of site conditions. This study is a follow-up on the Parsons MetalMapper demonstration that took place at the end of 2013. Both projects were coordinated with Herb Nelson from the ESTCP Program Office, Andrew Schwartz from USACE UXO Excellence Center in Huntsville, and Gregory Van from Parsons, who lead the MetalMapper study.

Data processing and analysis was mostly accomplished with the UXOLab software package, a suite of MatLab-based programs for digital geophysical mapping, target picking, inversion of single and multiple sources and classification. The software has been jointly developed with the University of British Columbia. It incorporates algorithms developed under SERDP projects and has been tested on over a dozen of ESTCP demonstrations.

EXECUTIVE SUMMARY

The Man-Portable Vector (MPV) sensor was demonstrated at a live site at the Former Waikoloa Maneuver Area on Hawaii in January 2014 as part of the ESTCP Live-Site Program for Munitions Response. This document reports on the data collection and the analysis that supported the digital geophysical mapping and classification that was done at the site.

The MPV is an electromagnetic induction (EMI) sensor designed for munitions detection and classification. Its handheld form factor provides enhanced portability and ruggedness relative to vehicular-based systems. The sensor head is a 50-centimeter diameter disk that includes a vertical transmitter and an array of five three-component receivers. The MPV supports two deployment modes: dynamic data collection along survey lines to establish a map of the UXO contamination; and static, cued interrogation of selected anomalies to acquire high-quality data for classification. Prior to this study, the technology had been demonstrated at five sites with the ESTCP: Yuma Proving Ground (2010), Camp Beale (2011), Spencer Range and George West (2012), and New Boston (2013). The technology has been tested for detection and classification with static and dynamic data under multiple environmental conditions: open field, low and high density forests and steep sided hills.

The Waikoloa site brought new challenges with the occurrence of multiple rocky outcrops that precluded use of vehicular-based systems, and soils with high magnetic remanent magnetization that caused sufficient geologic background noise to hide the response of buried objects. This study followed a demonstration with the MetalMapper by Parsons on the same Area TO20A where these challenges had already been encountered. The MPV presented an interesting alternative because its portability could be used to map the outcrops and its sensor configuration had been shown to have the potential to limit the adverse effect of magnetic soils. This demonstration was also the opportunity to test an alternative method for cued interrogation that utilized an additional set of two horizontal axis transmitter coils. The use of multiple coils provides three-dimensional (3D) excitation of buried targets from a single location and removes the need to move the sensor head to multiple locations around a target. The MPV operating software was also improved with near real-time inversion of the data to predict the buried object location and collect the most informative data for classification.

The MPV study focused on a 1.5-acre parcel where targets of interest included 37 mm projectiles, 60 mm and 81 mm mortars, as well as small and medium ISO that were seeded for quality control. The MPV was first utilized for a detection survey in which data were collected along straight lines with 0.5 m line spacing. The data were immediately analyzed and 450 anomalies were selected for cued interrogation in standard cued mode. The alternative 3D cued mode was tested on a subset of 120 anomalies selected among the most likely UXO.

The detection survey was generally successful at covering the entire site and detecting potential targets. One target was missed at a location where the data show no sign of any metallic object. Classification was independently applied to the standard and 3D cued data. In both cases all UXO were successfully classified with 81% clutter rejection in the standard method and 67% in the 3D method, where the novelty of the process guided a more conservative approach with additional training data and a later stop-dig decision point.

The demonstration met all performance objectives except one (on detection). Use of a handheld technology allowed mapping of the entire site. All detected anomalies were correctly classified. Results with the 3D cued interrogation mode suggest a promising faster and simpler method for characterizing anomalies that will be tested at future sites.

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1.0 INTRODUCTION

The demonstration at the Former Waikoloa Maneuver Area on Hawaii is one in the series of Environmental Security Technology Certification Program (ESTCP) demonstrations of classification technologies for Munitions Response (MR). This demonstration was designed to investigate the classification methodology at a site that included rugged terrain and significant geologic noise on EMI sensors due strongly magnetic soil. It took place in January of 2014.

This project proposed to demonstrate use of the Man Portable Vector (MPV) sensor for munitions response at Waikoloa. The MPV is a new-generation electromagnetic induction (EMI) technology packaged in a handheld form factor with the specific intent to extend advanced classification capabilities to sites with challenging surveying conditions and reach most human trafficable land locations at moderate cost (Figure 1).

The Waikoloa study followed a standard approach for classification at a munitions response site. It comprised of two stages: first, a full-coverage survey with an EMI sensor to map the munitions contamination and locate signal anomalies where potential threats might be located; second, re-acquisition of selected anomaly location to collect EMI data in cued interrogation mode, where data of the highest quality were collected for classification.

This project was also the opportunity to test technology transfer with the participation of the USACE and Environet, a local commercial operator. The field crews were trained to operate the technology, in particular to operate the software, to handle the sensor in detection mode such that no gaps are left, to recognize malfunctions, to assess data quality, and to interpret data displays in order to estimate the relative location of a buried target.

Figure 1: Detection with the MPV over rugged terrain with boulders at Waikoloa.

2.0 TECHNOLOGY

The MPV technology is based on electromagnetic induction sensing using one transmitter coil and multiple vector receivers in a handheld form factor. The sensor presented in this study is the second-generation prototype MPV, dubbed MPV2, which was deployed with the same hardware configuration at Spencer Range, Camp George West (ESTCP MR-201158) and New Boston (ESCTP MR-201228). A modified deployment method was also tested on a subset of the field anomalies.

2.1 TECHNOLOGY DESCRIPTION

2.1.1 The standard MPV

The MPV is a handheld sensor with wide-band, time-domain, EMI technology. The sensor head is composed of a single transmitter coil and an array of five receiver units that measure all three components of the EM field (Figure **2**). This second-generation MPV is specifically designed to (1) be man portable and therefore easy to deploy, maneuver and adapt to a survey environment, and (2) acquire data that is suitable for discriminating unexploded ordnance (UXO) from non-UXO targets. The MPV head is a 50-centimenter (cm) diameter transparent disk. The transmitter coil is wound around the disk and intermittently illuminates the subsurface. Five receiver units (cubes) measure the three orthogonal components of the transient secondary EM field decay with three air-induction 8-cm square coils – having multiple receivers generally improves the recovery of target parameters for classification (Gasperikova et al., 2007).

The MPV is a programmable instrument. The duration of the excitation and time decay recording can be adjusted to accommodate the specific needs of target detection and classification. The highest quality data is acquired when the sensor is static, such that multiple cycles of target excitation and response can be averaged or stacked to reduce the effect of noise sources. Use of long transmit-receive cycles (e.g., 8 msec or 25 msec time decay) can be applied to capture the time decay rate of the target response, which relates to the target type and can help make the distinction between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007). A data block consists of a number of repeats of the EMI receive-transmit cycle over a given time. For the detection survey, dynamic data are collected in full-coverage mode for digital geophysical mapping (DGM). Short data blocks, typically 0.1 sec, are applied so that the sensor can continuously move without smearing the data. There is a tradeoff between the duration of a transmit-receive cycle and the amount of stacking than can be done within a data block. Depending on the site conditions we use 2.7, 8.3 or 25 msec time decay, which allows respectively 9, 3 or just 1 full cycle. The default setting is 2.7 msec, which allows more stacking to reduce noise and false alarms, while still remaining some capability for screening fast decaying objects. In cued mode 25 msec decay length is preferred to capture the full decay spectrum of most target types.

The MPV is a handheld sensor. The sensor head weighs 13 pounds and the backpack-mounted data acquisition (DAQ) and batteries weigh approximately 30 pounds. In contrast, existing non-vehicular systems with multiple time channel measurement capabilities (e.g., Time Domain EM Towed Array Detection System [TEMTADS]) are required to be mounted on a cart platform due to the size and weight of the multiple coils of wire required for the transmitters and receivers.

The MPV sensor head is made of a transparent disk that contains a circular transmitter wound around the side and five 3D receiver cubes. The data acquisition system and batteries are mounted on a backpack frame caried by the second operator (Figure **2**). A touch-screen display is used to control survey parameters and acquisition events (At Waikoloa it was held by the second operator; it can also be mounted on the handle on the MPV boom). Positioning is derived from global coordinates obtained with a GPS rover and angles measured with an Attitude and Heading Reference System (AHRS) sensor. Both sensors are mounted on the top end of the MPV boom.

The MPV user interface has real-time data monitoring capabilities. The recorded data can be displayed to verify data quality and detect potential disturbances such as presence of magnetic soil or a malfunctioning receiver. The past and present sensor location is displayed on a map along with preset survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields with arrows. These features assist the field operator in efficient data collection, so that detection and classification data can be collected as part of the same survey, thus limiting the need to revisit an anomaly for further characterization.

Figure 2: The MPV technology components are shown in detection mode at Waikoloa.

2.1.2 The MPV3D configuration

An alternative deployment mode was tested at Waikoloa. Two orthogonal, horizontal-axis transmitter loops were fabricated by G&G Sciences with the concept of turning the MPV into a "mini-MetalMapper" by mounting the transmitters on top of the standard MPV2 head (Figure 3). The goal with this deployment mode is to simplify and speed up the cued interrogation process by eliminating the need to collect 5 or more measurements to achieve the transverse excitation of

a buried target; the transverse excitation is obtained from the horizontal-axis transmitters. This method also eliminates the requirement for a beacon boom, which was needed to provide accurate positioning between the multiple cued measurement. The revised system also simplifies the operator's task and they no longer need to interpret the different soundings to evaluate if the data are sufficient to cover the anomaly and characterize the target. With the 3D system, the data can be inverted on the spot to obtain an objective assessment of the data quality and target location (this computation was more complex with multiple soundings and beacon data and was not implemented for field use).

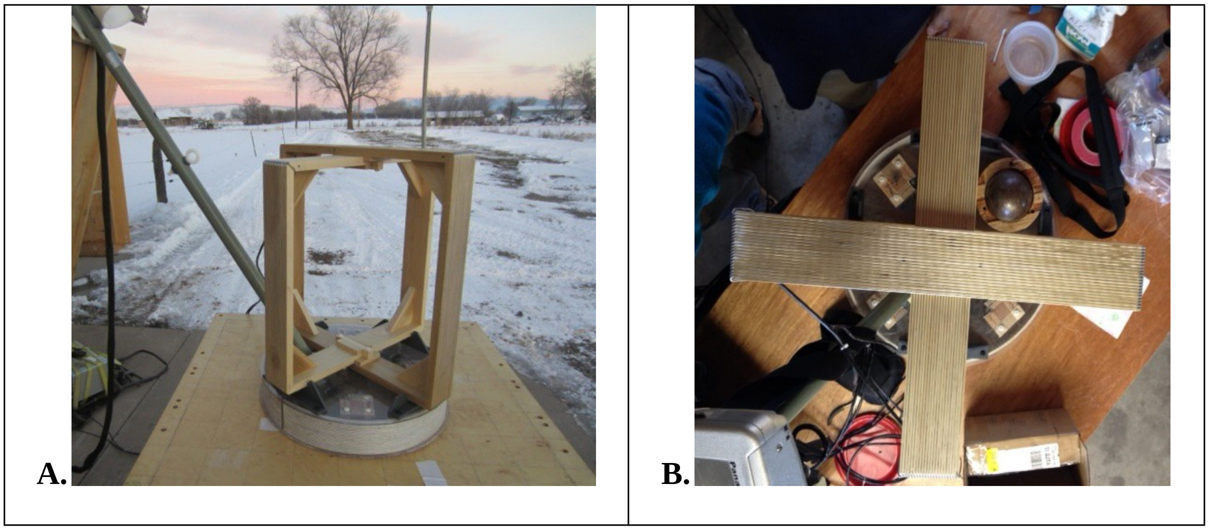


**Figure 3: MPV3D concept with two horizontal-axis transmitters placed on top of MPV2 head.
A: Side view of the 3D system (new transmitters made out of wood).
B: View from above of the orthogonal transmitters.**

2.1.3 Geolocation

The sensor requires positioning for detection and classification. Given that the entire site had open sky view, we used a Global Positioning System (GPS) Trimble R8 receiver unit and an Attitude and Heading Reference System (AHRS) XSens MTi unit that were attached to the MPV handle to provide centimeter-level positioning accuracy of the MPV sensor head.

2.2 TECHNOLOGY DEVELOPMENT

The project was initiated in 2005 under the Strategic Environmental Research and Development Program (SERDP) MM-1443. The project was led by Drs. Kevin O'Neill and Benjamin Barrowes with the Cold Regions Research and Engineering Laboratory of the Engineering Research and Development Center (CRREL, ERDC) in Dartmouth, New Hampshire (NH). The first MPV prototype was built in 2005-2006 with David George of G&G Sciences, Grand Junction, Colorado (CO). It was tested in 2007 at ERDC in a laboratory setting. Data analysis showed that stable target parameters could be retrieved and used for UXO classification.

The SERDP project was extended in 2008 to continue testing with the current Black Tusk Geophysics team. Field trials were done on a test plot to assess static and dynamic acquisition mode over buried targets and verify that stable target parameters could be recovered. The effect

of magnetic soil on EMI sensors was investigated with the MPV, for which we demonstrated that the particular geometric design and cube distribution could be used to defeat some of the adverse soil effects. The positioning system was evaluated for practical field use. We found that the ArcSecond laser ranger was impractical due to the requirement to maintain line-of-sight for three rovers and tedious calibration. The SERDP project was further extended in 2009 to test an alternative positioning system based on the beacon concept and prepare modification of the original MPV prototype for extensive field deployments. The sensor head was redesigned with lighter materials and a smaller head diameter to reduce weight and improve maneuverability while maintaining its expected performance (Lhomme, 2011b). Receivers were brought inside transmitter coil to reduce their exposure; transparent material was employed to see the ground through the unit. Actual fabrication of the new head began under that SERDP funding extension.

The ESCTP MR-201005 project had the objective to prove the concept of classification with the MPV at live sites. The MPV fabrication and integration of a new DAQ was completed before this second-generation MPV was demonstrated at Yuma Proving Ground UXO test site in October 2010. The technology was first demonstrated at a live site at former Camp Beale in June 2011 for cued interrogation in open field and in a moderately dense forest. In ESTCP MR-201158 the MPV was demonstrated at Spencer Range, TN in June 2102 for detection and dynamic classification in open field and cued interrogation in a forest, and at former Camp George West, CO in October 2012 on the side of a mountain with slopes up to 40%. In ESTCP MR-201228 the technology was tested in a dense forest at the New Boston Air Force Station in August 2013.

2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY

The MPV is the only available handheld sensor that can acquire multi-static, multi-component data on a wide and programmable time range. The MPV offers several key benefits:

- Hand-held form factor: The MPV can be deployed at sites where terrain and vegetation preclude use of heavier, cart-based systems. Portability can improve productivity in rough terrain. The system is easy packable and transportable;
- Five receivers simultaneously record three orthogonal components of EM field with near-perfect relative positioning among receivers. Multi-component, multi-axis design reduces number of soundings for target characterization and relaxes positional accuracy. Targets can characterized with as few as 5 soundings;
- Magnetic soil can be detected and defeated: The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil through techniques developed in SERDP MM-1414 and MM-1573;
- Fully programmable through field display: Graphical field-user interface controls acquisition parameters such as transmitter waveform characteristics, duration of excitation, number of measurement cycles, stacking and recorded time channels;
- Highly stable EMI components: Responses are directly predictable using standard EMI theory. Field tests verified that MPV components had imperceptible measurement drift and were largely insensitive to survey conditions;
- High resolution: Having several relatively small receivers (8-cm coils) allows localization and differentiation of individual anomalies better than large receivers (e.g., EM61), that tend to “smear out” secondary fields.

Portability has limitations: with a single transmitter, multiple soundings must be collected to characterize a target. Therefore, the MPV requires (1) an accurate positioning system for cued interrogation and (2) manual intervention to move the sensor, which reduces productivity relative to a multi-transmitter platform for which a single sounding is often sufficient. We here present a method to address this limitation by using the 3D deployment configuration.

3.0 PERFORMANCE OBJECTIVES

This project includes data collection in dynamic detection and cued interrogation, data analysis and user feedback for evaluation of the MPV technology. The specific objectives for each stage are detailed in Table 1. These objectives depend on the intrinsic data quality of the sensor, the deployment method and the ensuing data analysis and interpretation.

Table 1: Performance Objectives.

Performance Objective	Metric	Data Required	Success Criteria	Result
Data Collection Objectives				
Spatial coverage in detection survey	Extended footprint coverage	• Mapped survey data	98% coverage in open field	99.9% coverage
Station spacing	Distance between soundings	• Sensor location	80% of data points with 0.1 m spacing and 95% with 0.15 m	91% within 0.1m spacing and 99% within 0.15 m
Repeatability of Instrument Verification Strip (IVS) survey	Amplitude of EM anomaly Amplitude of polarizabilities	• Twice-daily IVS survey data	Factor of 2 on detection amplitude and 1.5 on target size	Factor of 1.5 on amplitude and size
Cued interrogation of anomalies	Instrument position	• Cued data	100% of anomalies where center of cued pattern is located within 0.5 m of anomaly pick	100%
Detection of all targets of interest (TOI)	Percent detected of seeded anomalies	• Location of seeded items • Anomaly list	100% of seeded items detected within 0.6 m halo	One missed seed
Production rate	Acreage and number of cued interrogations Pre-processing time	• Log of field work and data pre-processing time	Detection: 3 days max Cued mode: 100 anomalies/ day Pre-processing time <3 min per target	Detection: 2 days Cued mode: 150 anomalies/day Pre-processing 2 min/target
Analysis and Classification Objectives				
Maximize correct classification	Number of TOI retained	• Ranked dig list • Scoring reports by IDA	Approach correctly identifies the presence of 95% of TOI	100% correct classification
Maximize correct classification of non TOI	False alarm rate (FAR)	• Ranked dig list • Scoring reports by IDA	Reduction of clutter digs by 40% for 95% TOI	83% rejection of clutter for MPV2; 67% for MPV3D
Specification of no-dig threshold	Probability of correct classification of TOI and FAR at operating point	• Demonstrator threshold • IDA score	Specified threshold to meet above criteria	100%

Minimize number of unclassifiable anomalies	Number of "Can't Analyze" in cued data classification	• Ranked dig list	Reliable classification parameters for at least 90% of dig list	99% of anomalies are reliable
Correct location and depth of TOI	Accuracy of estimated target parameters for seed items	• Results of intrusive investigation • Predicted location	$\sigma Z < 0.10$ m σN and $\sigma E < 0.15$ m	$\sigma Z < 0.10$ m σN and $\sigma E < 0.15$ m

3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION

Dynamic detection survey should cover a maximum of the area of interest so that all detectable targets are illuminated. Targets are detectable if the transmitted field is sufficiently strong to reach the target and if the measured target response is sufficiently strong in return to exceed a given threshold. Simulations and analysis of field data suggest that there is negligible loss of detect-ability when a target is located within 10 cm of a receiver cube, therefore we use a 10 cm pixel-size to estimate the coverage rate.

3.1.1 Metric

The footprint of MPV detection survey is compared with the surface area for the region to be studied in dynamic detection mode.

3.1.2 Data requirements

The geographic coordinates for the perimeter of the region to be surveyed and the MPV survey track is utilized.

3.1.3 Success criteria and result

Success is met with 99.9% spatial coverage.

3.2 OBJECTIVE: STATION SPACING IN DETECTION MODE

This objective is meant to ensure that there is sufficient sampling along lines to not miss a target and to guarantee that the sensor is used within its survey-speed specifications.

3.2.1 Metric

The distance between soundings along lines is computed.

3.2.2 Data requirements

The sensor head location is derived from GPS and AHRS measurements.

3.2.3 Success criteria and result

Success is met with 91% of the data points within 0.1 m station spacing and 98% within 0.15 m, as shown in the cumulative histogram of Figure 4.

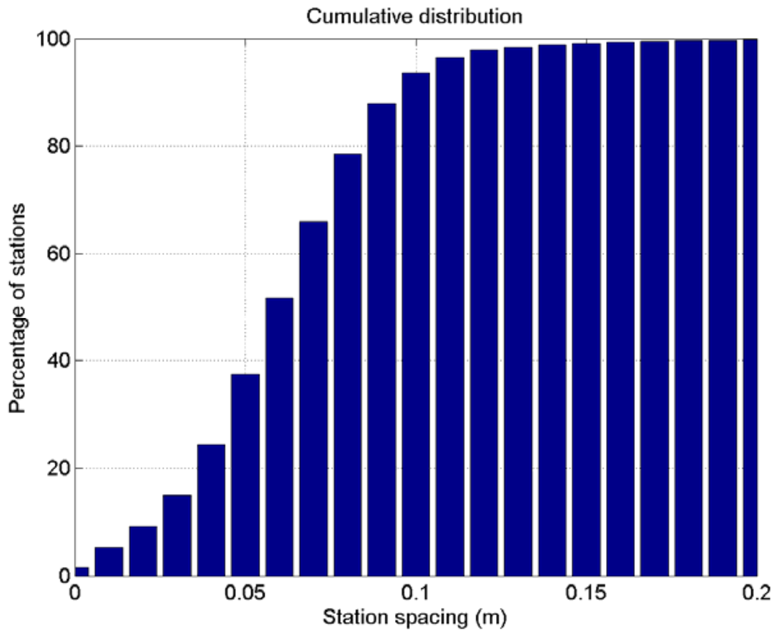


Figure 4: Cumulative distribution of the separation between consecutive measurements.

3.3 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS

Reliability of survey data depends on the stability of survey equipment. This objective concerns twice-daily verification on a test strip where metallic targets are buried. The IVS is surveyed in detection mode during the detection survey. The IVS anomalies were acquired in 5-point cued interrogation mode every day; the MPV3D configuration was tested at the beginning of the study (January 20-21) and verified during one day of data collection (January 31).

3.3.1 Metrics

The metric for detection relates to the amplitude of the maximum target response, defined as the norm of the total field on each receiver cube for the 0.5 msec time channel. The metric for cued interrogation is the target size, here defined as the time integral of the total polarizability between 0.1 and 4 msec.

3.3.2 Data requirements

IVS data are recorded for both detection and cued survey modes. The detection amplitude and target location is retrieved for each target. For the cued survey the data are inverted and the stability of the recovered target parameters is verified.

3.3.3 Success criteria and result

The detection requirement is for each target amplitude of each dynamic pass to be within a factor of 2 of the median value for that target. The criterion is met with a factor of less than 1.6 on the detection amplitude (Figure 12 in Section 7.1.1).

The objective for cued data is a factor of 1.5 on the target size parameter. Cued data were inverted and the recovered polarizability amplitude differed by less than a factor of 1.3 both for

the 5-point interrogation (polarizability curves are shown in Table 2, Section 7.1.1) and the 3D configuration (Table 3 in Section 7.1.1).

3.4 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

The reliability of cued data depends on acceptable instrument positioning during data collection in relation to the actual anomaly location.

3.4.1 Metric

The metric for this objective is the percentage of anomaly peaks that are located within the acceptable distance to the center of the cued interrogation survey of each anomaly.

3.4.2 Data requirements

The demonstrator records the location of their instrument for each cued anomaly interrogated and verifies that the anomaly is covered by the survey pattern. Verification is done while still on site so that anomalies can be re-acquired if needed.

3.4.3 Success criteria and result

The objective is to center the cued interrogation within a distance of 0.5 m from the picked anomaly location. The objective was met, with less than 0.2 m deviation from the picked location for all MPV2 and MPV3D anomalies (Figure 15 in Section 7.3.1).

3.5 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Quality data should lead to high probability of detecting all TOI at the site.

3.5.1 Metric

The metric for this objective is the percentage of seed items that are detected using the specified anomaly detection threshold.

3.5.2 Data requirements

The demonstrator submits a detection list to the Program Office for evaluation.

3.5.3 Success criteria and result

All quality control seeds were detected. However, one quality assurance seed was found to be missing upon examination of the ground-truth information. The seeded item was a 60 mm mortar at 0.4 m depth. The dynamic data show no sign of any metallic object near that location (see analysis Section 7.2). No cued data were collected at that location.

3.6 OBJECTIVE: PRODUCTION RATE

This objective concerns the time taken for data collection and pre-processing of field data.

3.6.1 Metric

The metrics are the mean daily survey rates in terms of acreage for dynamic survey and number of targets for cued interrogations, and the mean pre-processing time per anomaly.

3.6.2 Data requirements

The acreage and number of surveyed anomalies and the pre-processing time were recorded on every day.

3.6.3 Success criteria and result

The goal was to achieve a daily average of at least 0.7 acre for detection and 100 anomalies for cued interrogation, and pre-process each cued anomaly in less than 3 minutes. The dynamic survey was completed in 13 hours split over 3 days because of weather. Given that the survey area was 1.5 acres and assuming a full day of field data collection of 6.5 hours, the average production rate is better than 0.75 acre per day.

Similarly, the cued interrogation of 458 anomalies in standard MPV2 mode was completed in 17 hours over 5 days. Without weather delay it would have taken less than 3 days, with an average of 150 anomalies per day. The cued interrogation of 139 anomalies with the MPV3D was completed in 3.5 hours. In terms of pre-processing, cued measurements were treated in less than 2 minutes per anomaly. Supporting material is presented in Section 7.4.

3.7 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

This is one of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms, targets were classified with high efficiency. This objective concerns the component of the classification problem that involves correct classification of TOI.

3.7.1 Metric

The metric for this objective is the number of items on the anomaly list for a particular sensor that can be correctly classified as TOI by each classification approach.

3.7.2 Data requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

3.7.3 Success criteria and result

The objective was met with 100% of the TOI correctly labeled on the ranked anomaly list for each of the independent analyses made with the standard 5-point MPV2 and the MPV3D.

3.8 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

This is the second of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms, targets were classified with high efficiency. This objective concerns the component of the classification problem that involves false alarm reduction.

3.8.1 Metric

The metric for this objective is the number of items on the sensor dig list that can be correctly classified as non-TOI by each classification approach.

3.8.2 Data requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

3.8.3 Success criteria and result

The objective was to reject more than 40% of the non-TOI items while retaining at least 95% of the TOI on the dig list. The MPV2 study included 12 TOI and 85 pieces of clutter, of which only 14 were placed on the dig list, which amounts to 83% clutter rejection rate.

The MPV3D study covered 10 TOI and 42 non-TOI, of which 14 were dug, for a clutter rejection of 67%. This is a strong result for the MPV3D given that this was the first time that this type of data was collected and analyzed and that some unnecessary digs were required for training and calibration.

3.9 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

In a retrospective analysis it is possible to tell the true classification capabilities of a classification procedure based solely on the ranked anomaly list submitted by each demonstrator. In a real-world scenario, all targets may not be dug so the success of the approach depends on the ability of an analyst to accurately specify their dig/no-dig threshold.

3.9.1 Metric

The probability of correct classification of TOI, P_{class}, and number of false alarms, N_{fa}, at the demonstrator-specified threshold are the metrics for this objective.

3.9.2 Data requirements

The demonstrator prepared a ranked anomaly list with a dig/no-dig threshold indicated. IDA personnel used their scoring algorithms to assess the results.

3.9.3 Success criteria and result

The objective of rejecting more than 40% of the non-TOI items while retaining 95% of the TOI at the demonstrator-specified threshold was met. For the MPV2 study, the last TOI was found after digging 7 non-TOI items, which means that 89% of the clutter could have been rejected. At the stop-dig point the clutter rejection was 82%.

For the MPV3D study, the last TOI was found after 8 pieces of clutter were dug, which is 81% clutter rejection. The stop dig point was manually selected to include 6 other pieces of metal that had smaller size but similar shape (polarizability decay curves) as the smallest TOI to hedge against the risk of under-predicting the target size because of the effect of magnetic soil. The clutter rejection rate was 67%.

3.10 OBJECTIVE: MINIMUM NUMBER OF UNCLASSIFIABLE ANOMALIES

Anomalies for which reliable parameters cannot be estimated cannot be classified by the classifier. These anomalies must be placed in the dig category and reduce the effectiveness of the classification process.

3.10.1 Metric

The metric is the number of anomalies that cannot be analyzed by our method.

3.10.2 Data requirements

The submitted dig list specifies those anomalies for which parameters could not be reliably estimated.

3.10.3 Success criteria and results

The objective was to be able to classify at least 90% of the anomalies. The objective was met with only 1 anomaly labeled as "can't analyze" in the MPV2 study, and none for the MPV3D.

3.11 OBJECTIVE: CORRECT ESTIMATION OF LOCATION AND DEPTH

Correct target classification relies on the capability to extract valid target parameters. Accurate TOI location is also important for safe and efficient site remediation.

3.11.1 Metric

The metric is the difference between observed and predicted depth and geographic location.

3.11.2 Data requirements

Target location and depth are recorded and compared to ground-truth validation measurements. This objective requires accurate ground truth documentation.

3.11.3 Success criteria and result

Depth should generally be predicted within 0.10 m and geographic location within 0.15 m. For the MPV2, the depth was recovered within 0.05 m for all TOI and the location within 0.15 m for 9 out of 12 TOI and less than 0.22 m for all TOI. For the MPV3D the depth was recovered within 0.05 m for all TOI and the location within 0.05 m for 8 out of 10 TOI and within 0.22 m for 2 TOI. We find 2 common position outliers for the MPV2 and MPV3D, which may suggest inaccuracy in the ground truth rather that the model prediction; the positional objective could be relaxed to 0.20 m while preserving the reliability of classification given that high confidence matches to the correct library items were found for all outliers. The objective is met. Supporting material is presented in Section 7.3.2.

4.0 SITE DESCRIPTION

4.1 SITE MAP

The site is on the northwest side of the Big Island of Hawaii between Waikoloa Village and Waimea. The study area is Task Order Area 20, for which a map is presented in Figure 5. A detailed description of the site can be found in Parsons demonstration report (Van et al., 2015) for the MetalMapper study that took place in the Fall of 2013.

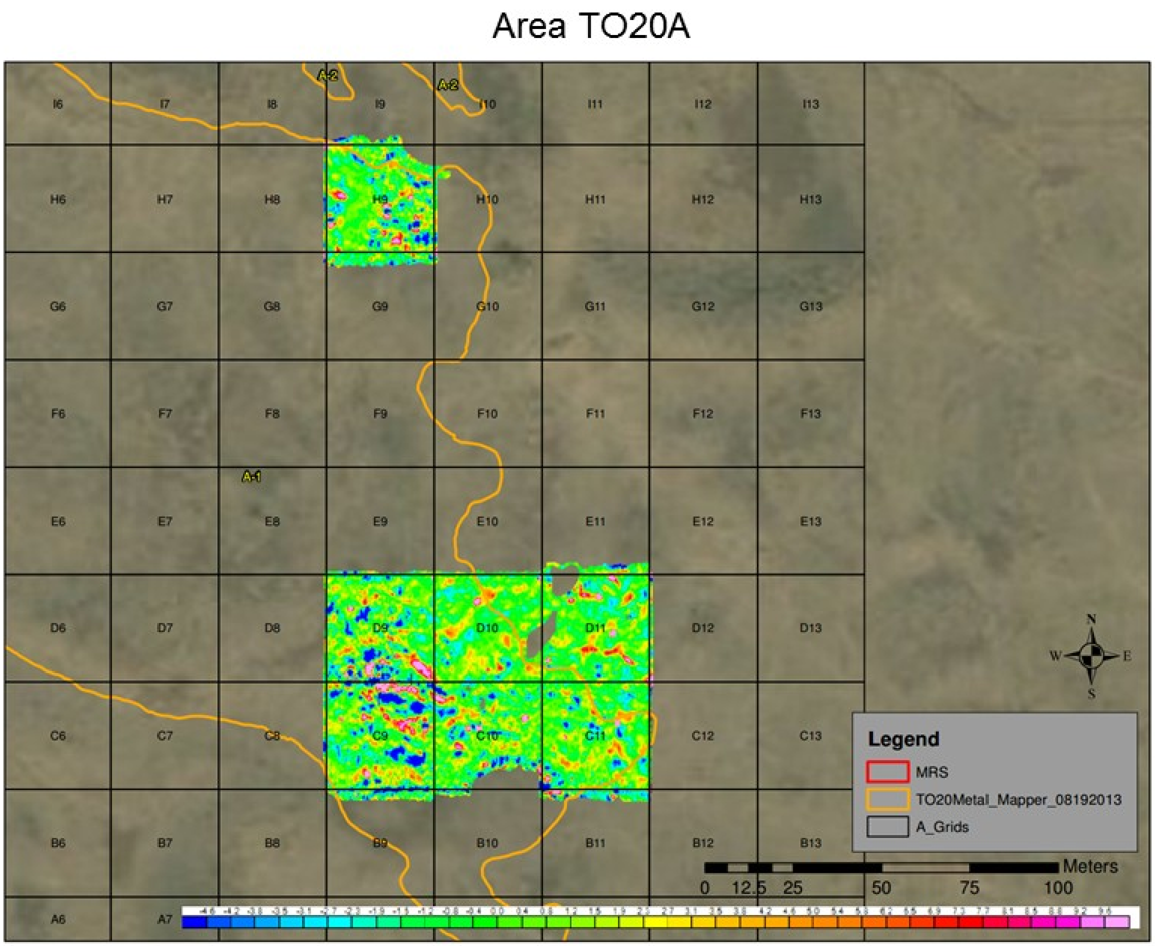


Figure 5: Survey area map. Grids C9-C11 and D9-D11were selected for the study.

4.2 MUNITIONS CONTAMINATION

Suspected munitions included:

- 60-mm and 80-mm high explosive mortars
- 75-mm, 105-mm, and 155-mm projectiles
- 2.36-inch rocket propelled anti-tank rounds
- US MK II hand grenades
- Rockets
- M1 anti-tank land mines
- Japanese ordnance

5.0 TEST DESIGN

5.1 EXPERIMENTAL DESIGN

The goal of the study is to demonstrate detection and classification with the MPV at a site with rocky outcrops, where access is difficult, and conditions of significant background noise from highly magnetic soils. The key components for a successful technical realization are collection of high quality data; detection of all anomalies related to UXO by choosing an adequate detection approach and threshold; extraction of reliable parameters for characterizing all detected anomalies; and application of the adequate classification approach for selecting those items that can remain in the ground and those that must be excavated.

Detection and classification were validated by seeding quality control targets that had to be detected and correctly classified, and by excavating most of the detected items. Given that the magnetic soil caused a large number of false detection events, the validation process was supported by a Minelab metal detector to reject some of the clear soil events and help focus the intrusive investigation on anomalies caused by the presence of metallic objects. The intrusive results were compiled to create a master list of anomaly locations.

Classification was based on cued data collected near the master list anomaly locations. Analysts had the opportunity to ask for training data, ground-truth information on their selection of anomalies and to calibrate their classification approach before submitting their ranked dig lists. Ground-truth information on the priority digs were revealed to the analysts, who had the opportunity to add more digs to their list. Their final lists were scored by the Institute of Defense Analysis for comparison with other analysts and assessment of the entire demonstration process.

5.2 SYSTEM SPECIFICATION

5.2.1 Data acquisition

For cued interrogation mode the system is set for 25 msec excitation and 25 msec recording of EMI transients (100 msec per cycle). This is accomplished by setting the acquisition parameters to 0.9 seconds (sec) data blocks and 9 repeats. Station time is set to 6.3 sec by stacking 7 data blocks (effectively 9 x 7 = 63 cycles are averaged). Digital receivers use a 4 microsecond sampling rate. The data are recorded with 133 logarithmically-spaced time gates (5% gate width) from 0-25 msec. Dynamic survey is set with 8 msec time decay and short 0.1-sec data block to reduce smearing of the signal by sensor motion.

5.2.2 Positioning and navigation

The dynamic area has open sky and positioning is based on the GPS. In cued mode local positioning is achieved with the beacon system, though the GPS data are still recorded to verify beacon accuracy whenever enough satellites are visible, in particular at the IVS and in the open-field area. The GPS is a Trimble R8 that is mounted on the opposite end of the MPV handling boom. The GPS is also used to locate pre-programmed flag locations. An XSens MTi orientation sensor is mounted near the GPS to predict the sensor head location relative to the GPS.

5.3 CALIBRATION ACTIVITIES

Calibration is designed to verify correct sensor operation and calibrate the recorded sensor response over known targets. A sample set of the expected targets were calibrated with test pit measurements. Each sample was successively placed inside a clutter-free training pit and

surveyed in cued interrogation mode. A minimum of four different orientations and one depth per target were acquired to train feature extraction and classification methods. Data were inverted on that day to verify the stability of the recovered target parameters.

Dynamic data were acquired over a 37 mm projectile for the purpose of confirming the detection threshold procedure with empirical evidence.

The IVS was surveyed for calibration and sensor verification in dynamic detection and cued interrogation modes. The IVS was surveyed multiple times for training in both modes, and twice daily in the collection mode of the day for verification. The detection data were analyzed to verify spatial coverage and the stability of the EMI responses, thus providing an indirect check on the data collection procedure and on the sensor components. The amplitude of the target responses were also used for calibration against the detection threshold. The dynamic data were inverted to recover the dynamic polarizabilities of the buried targets. These were used for detection simulations and classification of dynamic data. The cued data were also inverted to recover the static polarizabilities, verify their stability, and provide training data for classification.

Geologic background measurements in cued mode were acquired for every anomaly on the first day by identifying “quiet” areas, which can be recognized with the arrows display in detection mode and by examining the recorded decay curves in static mode. Data were analyzed to quantify the spatial and temporal variability in background noise due to soil magnetization. After the first day backgrounds were collected for every sixth anomaly.

5.4 DATA COLLECTION PROCEDURES

5.4.1 Detection survey

Detection survey is performed by walking along pre-defined survey lines. The sensor has an effective detection footprint of 0.7 m although the largest cube separation is 0.47 m (between cube centers). To ensure full coverage the detection survey was run at 0.5-m line spacing. Practically, field operators laid survey ropes on the ground at 1-m spacing and used the lines to guide the exterior side of the MPV sensor head (Figure 6).

Figure 6: Dynamic survey along lines. The sensor head is held sideways. The operator follows straight lines.

5.4.2 Cued interrogation

Similar to previous demonstrations, cued interrogation soundings are collected around the marked target location (ground paint or flag). For the standard 5-point measurement, the first sounding was acquired at the picked location, followed four additional measurements arranged in a square pattern, as shown in Figure 7. For the MPV3D, the sensor was placed at the picked location. The data were immediately inverted. If the recovered target location was offset by more than 0.2 m, a second measurement was acquired at the new predicted location.

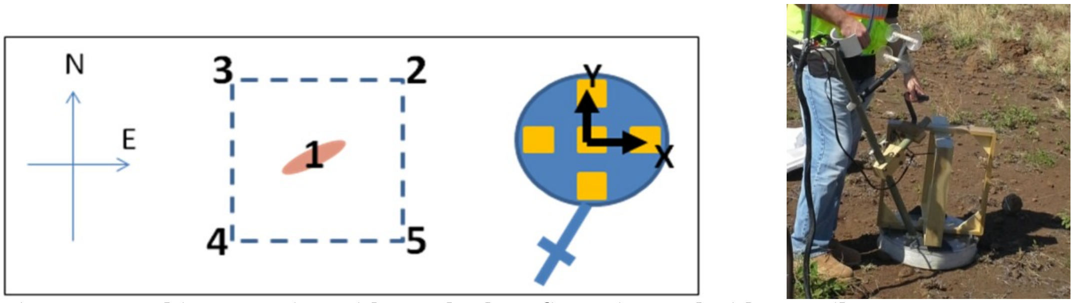


Figure 7: Cued interrogation with standard configuration and with 3D coils.
Left: In standard mode, five measurements are collected around the location of the anomaly pick, starting at that location and following in a square pattern with 0.5-0.7 m separation.
Right: With the 3D coils the first sounding takes place at the picked location. The data are inverted and a second measurement might be taken in the case of large predicted offset.

5.4.3 Positioning and navigation

The RTK GPS was used in open field to locate the sensor for mapping, and for re-acquiring targets for cued interrogation. The GPS data were ingested by the DAQ to indicate, in real-time, the sensor location. Detection lines were laid on the ground and preprogrammed and loaded in the DAQ to track the real-time spatial coverage on the control display. Flagged anomalies were also preset so that the GPS could be used for navigation to these anomalies.

5.4.4 Quality checks

<u>A general check</u> on proper operation was verified every time the instruments are powered on. The positioning systems were checked by waving the MPV head and verifying on the screen display that the reported position and orientation numbers as well as the location map were being updated and vary as predicted. The EMI elements were checked by acquiring data in dynamic or static mode, depending on the stage of the project. The operator verified that the "dancing arrows" display was updated in response to variations in the EM environment, that signals were appearing in the signal time-decay display (Figure 8) and that a file was being written.

<u>Battery change</u> was accompanied with a basic system check although the DAQ was not necessarily shut down (hot-swap of the batteries). A background soil measurement and an in-air measurement were acquired in the current survey mode (dynamic or static) before and after the battery swap. The operator checked the display for anomalous behavior. The data were later examined on a workstation to identify any sensor drift. In addition, background measurements for the soil response, with the sensor on the ground, and the in-air response were frequently acquired. The former test was to document the variability in the soil response and ensure that the most relevant background was applied – a magnetic soil response would mostly affect the late time data and may appear similar to the presence of a large deep target. The in-air measurement was designed to capture the intrinsic sensor response as a function of the battery power, which varies as the battery drains out. That response is particularly important at early time, during the 0.3 msec after the transmitter turns off, when a large inductive response is observed in the Z-component receivers due to their coupling with the Z-axis transmitter (the so-called "transmitter ringing" effect).

<u>Dynamic acquisition</u> was continuously monitored by verifying that the sensor location map, the positioning data table and the dancing arrows were being updated. In particular, the map would show a sensor track that covered the survey line without any gaps; a pop-up window

would appear if data errors were encountered; the dancing arrows should move around in response to changes in the sensor clearance or the presence of metallic objects. The second operator, who carried the backpack, was also involved in quality control by verifying that the front operator was keeping the sensor head close to the ground, covering the entire line and keeping a somewhat uniform pace.

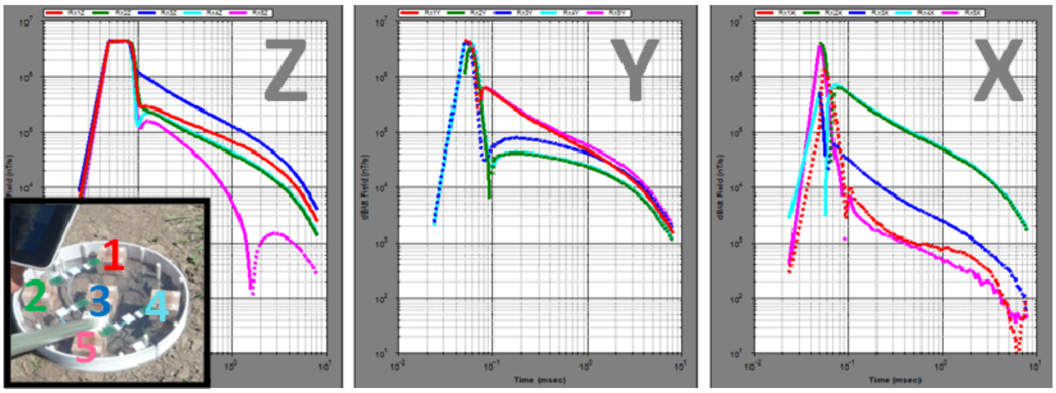


Figure 8: Typical target response when the MPV head is placed directly above a buried target. The Z-component data shows that target is closest to the center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in cube 5 resembles background. The Y data confirm that target is buried between front and back cubes (1, 5) and X data confirm that target is located between side cubes 2 and 4.

<u>Cued interrogation</u> followed a specific protocol. Each sounding was displayed immediately after acquisition to verify proper sensor operation and correct characterization of the buried target. The operator verified that receivers were properly operating by examining data decay curves (Figure 8) and the "dancing arrows" display. Any abnormal sounding were deleted, reacquired at the same location and flagged in field notes to differentiate it from acceptable soundings. If receiver failure occurred the survey would be stopped until a solution was found. Correct characterization of an anomaly followed a series of steps:

- The first sounding required particular attention to verify that the signal source originated right below the marked location. There can be an offset between the picked anomaly location, where the MPV would be placed, and the apparent target location that is predicted by the current MPV data – this can arise from positional error, choice of a target picking algorithm, or the presence of multiple targets. In case of large apparent offset the operator was expected to try and interpret the cued interrogation data to locate the signal source and acquire additional soundings if necessary;
- Anomaly coverage was verified by ensuring that the furthest receiver measured background. If residual signal from the target remained, then additional soundings were collected to ensure full coverage of the anomaly spatial decay. For instance, if the MPV front receivers showed above-background signal when the MPV was placed in position 2 of Figure 7, then a sounding was to be collected North of the middle of positions 2-3. If a nearby, interfering target was detected while being un-flagged for cued interrogation, then supplementary soundings are acquired to improve characterization of the two sources.

<u>Off-site data quality review</u> was performed on a daily basis by importing dynamic and cued data. The geophysicist loaded up the data to verify that positioning and EMI sensors were properly functioning, that noise levels were normal, that positioning systems (GPS and beacon)

yielded realistic positions and that spatial coverage was sufficient. In particular, the analyst checked for gaps in the dynamic detection map, and verified that anomalies were fully covered in cued mode. If problems occurred, then causes were investigated and the affected survey lines or anomalies were resurveyed if necessary.

The last check was verification that all targets had been visited. In the open field we kept track of all anomalies by having pre-programmed their GPS coordinates and displaying their location on the sensor display map. Each visited target was automatically marked on the map. In the forest we used manual field notes and a spreadsheet to keep track of the number of anomalies per line and make sure that all anomalies were visited.

5.4.5 Data handling

Data were stored as .tem files on the DAQ and converted to .csv files before every battery change. We kept a copy of all .tem and .csv files on the DAQ, on a portable hard-disk drive and on the field laptop that was used for reviewing the data.

The back operator documented the survey by noting target names and file numbers in addition to any remarks made by the principal operator. Field notes were digitized every day by taking pictures of the notes and filling out a spreadsheet that was used for pre-processing.

6.0 DATA ANALYSIS

The data analysis process followed standard methods that have been tested and validated in previous ESTCP demonstrations. The following sections provide general guidelines. Stand-alone reports are presented in the report appendices for detection (Appendix B), classification with the standard MPV 5-point survey (Appendix C) and the MPV3D configuration (Appendix D).

6.1 PREPROCESSING

The DAQ recorded data streams from the sensor head, the attitude sensor and GPS. Each static sounding or segment of a line search was saved into a .tem binary file, which was later converted to a .CSV format file without any data alteration. The files were verified, renamed and packaged for delivery and distribution.

For the detection analysis, dynamic data were merged and the AHRS and GPS data were combined to predict the receivers locations. For each EMI data block in dynamic and cued mode, the receiver data were divided by the maximum transmitter current amplitude for that data block. This process compensates for fluctuations in transmitter battery power by normalizing the response to a unit transmitter excitation.

For cued data pre-processing was simplified by the absence of beacon data and improvements in the data packaging, by which multiple cued measurements over an anomaly can be saved in the same file (in the past each measurement made for a separate file). Background measurements were analyzed to define the background response to be subtracted from the cued data. The resulting data were visually validated.

6.2 TARGET SELECTION FOR DETECTION

Dynamic survey data were recorded, filtered and interpreted to produce a digital map of the area and identify anomalies that require further investigation. Anomalies were retained when their signal amplitude exceeded a given threshold. That threshold was derived from numerical simulations of the worst case scenario for the expected targets and validation with empirical data that were collected on site. A detection memorandum detailing our analysis process and target picking method was submitted to the ESTCP Program Office (Appendix B).

The detection threshold was derived from simulations of the response for a 37 mm projectile and confirmed with calibration data acquired in dynamic mode over a 37 mm projectile and equivalent targets supplied on site. A late time channel at 1.66 msec was chosen as a compromise between weaning out fast-decaying clutter while keeping high signal relative to the background noise. The Z-component data was mostly used for the detection process and for producing a map. Each receiver cube was processed as an independent survey line with an algorithm that picked targets along line profiles and kept anomalies for which there were at least two consecutive data points exceeding the threshold. The line profile algorithm was preferred to the gridded image detection method because the latter is more sensitive to positional error and data gaps, which can create grid artifacts. A detection list with geographic locations and anomaly labels was submitted to the ESTCP Program Office. There was no report of a missed seed. The detection map for the filtered Z-component data at the 1.66-msec time channel is shown in Figure 9. The unfiltered map is presented in Figure 10 to illustrate the rocky outcrops (blue areas with low background signal) and the highly magnetic areas.

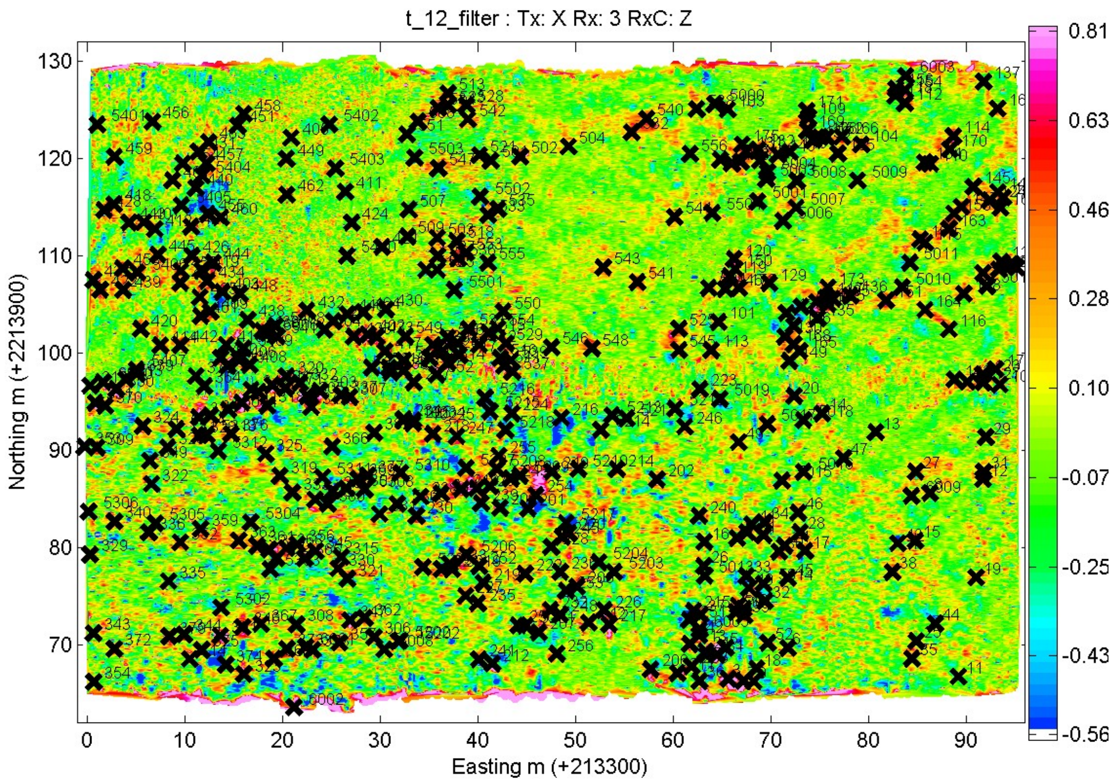


Figure 9: Detection map and MPV anomaly-pick locations for the demonstration area.

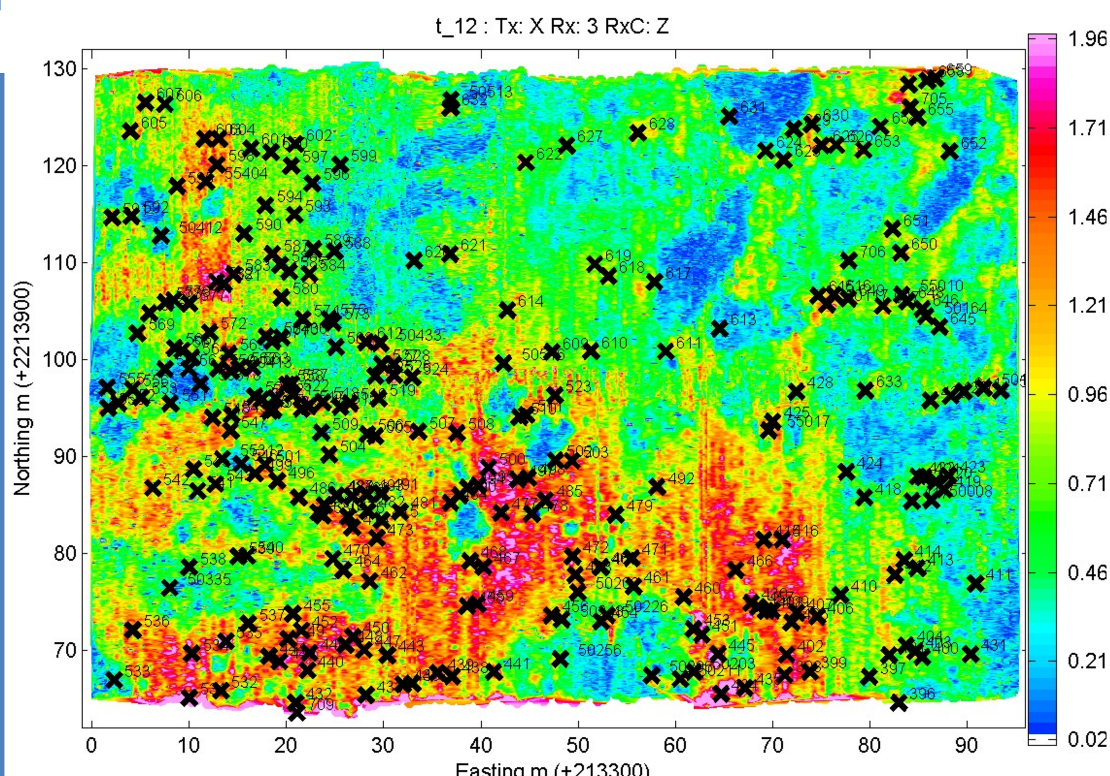


Figure 10: Map of unfiltered MPV detection channel and intrusive dig locations.

6.3 PARAMETER ESTIMATION

As in previous ESTCP demonstrations, data analysis was performed in UXOLab, a MatLab-based software package developed by BTG with the University of British Columbia in Vancouver. Data are inverted using a three-dipole instantaneous polarization model (Pasion and Oldenburg, 2001). The target polarizability decay parameters are the main features for the ensuing classification. Inversion setup parameters such as noise estimation are generally decided upon examination of training pit data and noise estimates on the IVS and in the field. Solutions with one or multiple targets are generated for every selected target. Decisions regarding the number of targets at a given location are made through statistical classification by prioritizing the most munitions-like solutions. Inversion results are reviewed by an experienced geophysicist to identify any potential issues with the inversion setup or with the data, and select data subsets as required for fitting all detected anomalies (masking).

6.4 TRAINING

Statistical classifiers are trained on a library of target features that has been accumulated during the previous surveys and new features associated with local targets. Measurements collected over the training pit provide that local information. Munitions are studied at various orientations so that their parameter variance can be estimated.

After testing of the classifier, additional training data may be requested to the ESTCP to obtain information about particular targets. Targets may be remarkable because there they belong to a cluster of unknown targets with similar features. Targets may stand out for having particularly large inferred size. This process of requesting training data is iterated until sufficient confidence in the classifier is attained.

6.5 CLASSIFICATION

As for past ESTCP demonstration studies, the following guiding principles were applied:

- *Selection of features:* By analysis of the training data, those features that contribute to separation of the different classes (comprising UXO types and clutter) are selected. Our experience shows that the three sets of instant polarizability decays generally yield successful classification with the MPV (and other sensor data). The data are inverted in different manners, using single-target and multiple-target inversions and eventually different noise parameters or mask sizes. Therefore, multiple sets of features can be extracted from the same anomaly and the model that most likely resemble a TOI is automatically selected through classification;
- *Choice of classification algorithm:* Methods are elaborated through analysis of the training data. Past studies have been successful using a Library Fit method or a Support Vector Machine (SVM) classifier. These methods can be combined or applied multiple times with different parameters;
- *Number of UXO-classes or reference items*: A library of reference items found in previous studies is augmented with local items measured on a test pit at the site. The library includes polarizability decay curves that are intrinsic to each library item. The reference library is reduced by retaining the expected targets of interest in addition to reference items for which there is a close match with polarizabilities in the field data;

- *Classification:* Anomaly labels are placed in a prioritized dig-list by using the classifier to compute probabilities of class membership for unlabeled feature vectors. The most likely TOI is reported in the dig sheet.

The classification approach was finalized after examination of the recovered target parameters and analysis of local conditions. A ranked anomaly list was prioritized according to the likelihood of being UXO and formatted as in Figure 11. The first items on each anomaly list were those targets for which reliable parameters could not be extracted and therefore had to be dug. Next were the items that were considered as "high confidence' munitions, ranked according to decreasing confidence that the item was hazardous. Any items that were analyzed without reaching an unambiguous classification decision were placed next on the anomaly list. Finally, all items that were confidently classified as non-hazardous were ranked by their confidence.

Initial Ranked Anomaly List

Anomaly ID	Category	Dig on First Pass	Type	Comment
2498	-1	1		Training Data
247	-1	1		
1114	0	1		Can't extract reliable parameters
69	1	1	105	
811	1	1	48	High likelihood TOI
313	1	1	37	
883	2	1		
1642	2	1		Unable to classify
713	2	0		
406	3	0		
...	3	0		High likelihood not TOI
...	3	0		
...	3	0		
...	3	0		
...	3	0		
...	3	0		

First Pass Threshold

Final Ranked Anomaly List

Anomaly ID	Category	Dig	Type
2498	-1	1	
247	-1	1	
1114	0	1	
69	1	1	105
811	1	1	48
313	1	1	37
883	1	1	
1642	1	1	
713	1	1	57
406	3	0	
...	3	0	
...	3	0	
...	3	0	
...	3	0	
...	3	0	
...	3	0	

Final Threshold

Figure 11: Format of prioritized anomaly list to be submitted to ESTCP Program Office.

7.0 PERFORMANCE REVIEW

7.1 REPEATABILITY

The technology was tested at the beginning and end of each field day on the IVS, where a shotput (sphere), a large ISO, a medium ISO and a small ISO were buried (from South to North). There was an additional small ISO that was buried too deep to be detected and characterized. We omit it in this analysis.

7.1.1 Dynamic IVS

The IVS was surveyed in dynamic mode during the days with detection survey. The data were analyzed to verify the stability of the anomaly locations and amplitudes, based on the 0.5 msec time channel. The analysis is summarized in Figure 12. The detected peak location for each IVS target, shown in the first column of panels, remains within 0.4 m of the average location. The amplitude of the peak signal, in the second column of panels, remains within a factor of 2 of the median amplitude value. All data quality objectives were met for the dynamic IVS.

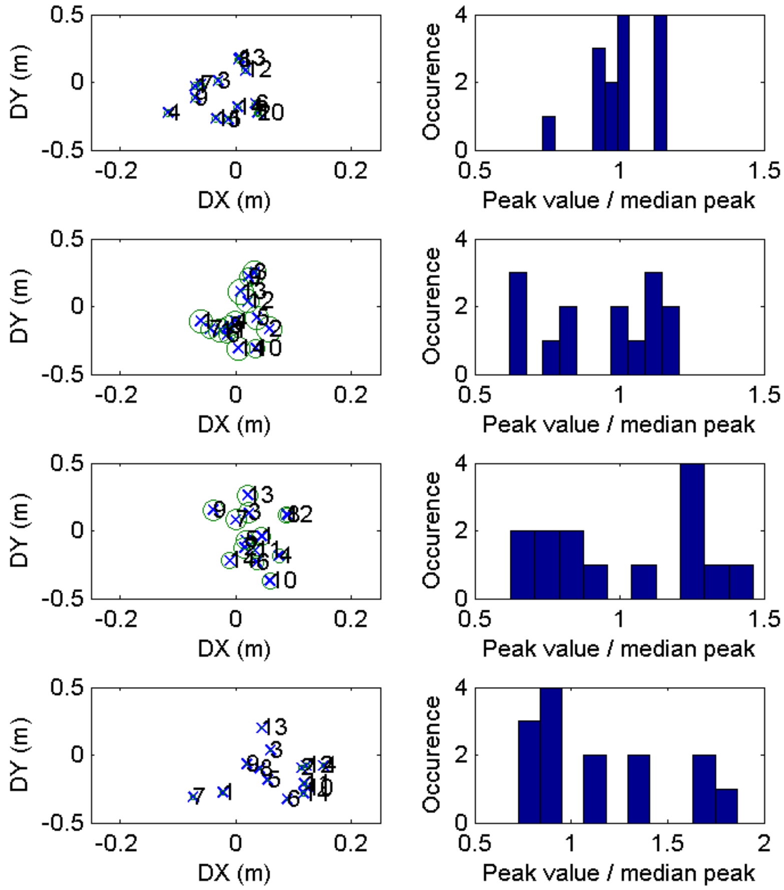


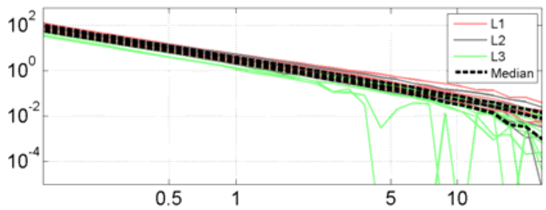
Figure 12: Analysis of the dynamic detection data for the IVS based on 0.5 msec channel. Each row corresponds to an IVS target, from North (top) to South (bottom). Column 1: Local offset between peak detection and target location; Column 2: Amplitude of peak value relative to median value of peak amplitude for each target.

7.1.2 Cued IVS

The IVS targets were interrogated in cued mode every day. Data were inverted to verify the stability of recovered polarizabilities. The metric was based on the predicted target size, defined as the integrated total polarizability from 0.1 to 4 msec. The success criterion was to predict the size within a factor of 1.5 of the median value. Recovered polarizabilities are presented in Table 2 for the MPV2-5-point and in Table 3 for the 3D system. For each item and survey configuration the range of predicted size was calculated. The results show that the predicted size remained stable throughout the demonstration study and ranged between a factor of 1-1.4. The highest stability was obtained with the 3D configuration.

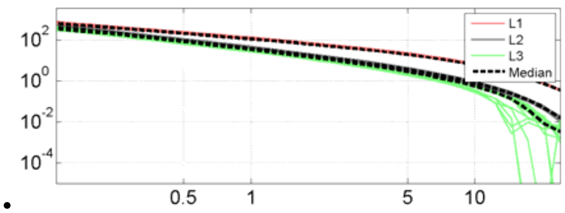
Table 2: Stability of the IVS polarizabilities for the 5-point cued measurements.
Each panel shows the polarizability amplitude (arbitrary units) as a function of time (msec). The targets are a sphere (1), a large ISO (2), a medium ISO (3) and a small ISO (4). For each target, the top panel shows all 3 polarizability decay curves for all cued interrogations as well as the median value for the entire project.

1.



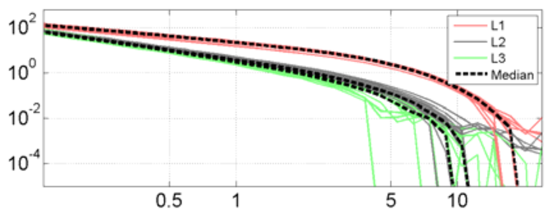
Size factor from 1-1.30

2.



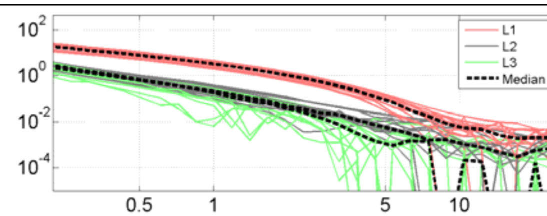
Size factor from 1-1.20

3.



Size factor from 1-1.36

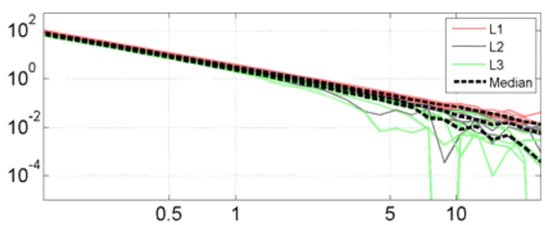
4.



Size factor from 1-1.38

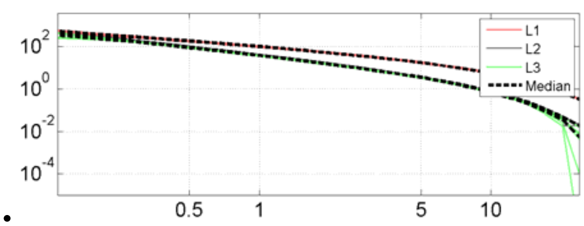
Table 3: Stability of the IVS polarizabilities for the cued MPV3D data.

1.



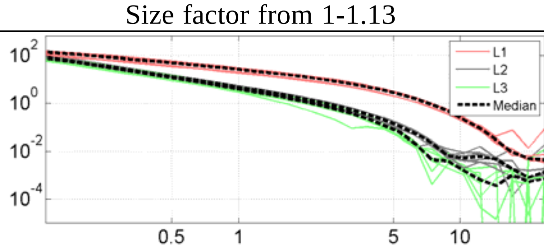
Size factor from 1-1.13

2.



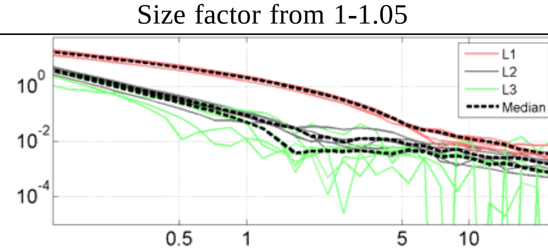
Size factor from 1-1.05

3.



Size factor from 1-1.21

4.



Size factor from 1-1.39

7.2 DYNAMIC DATA

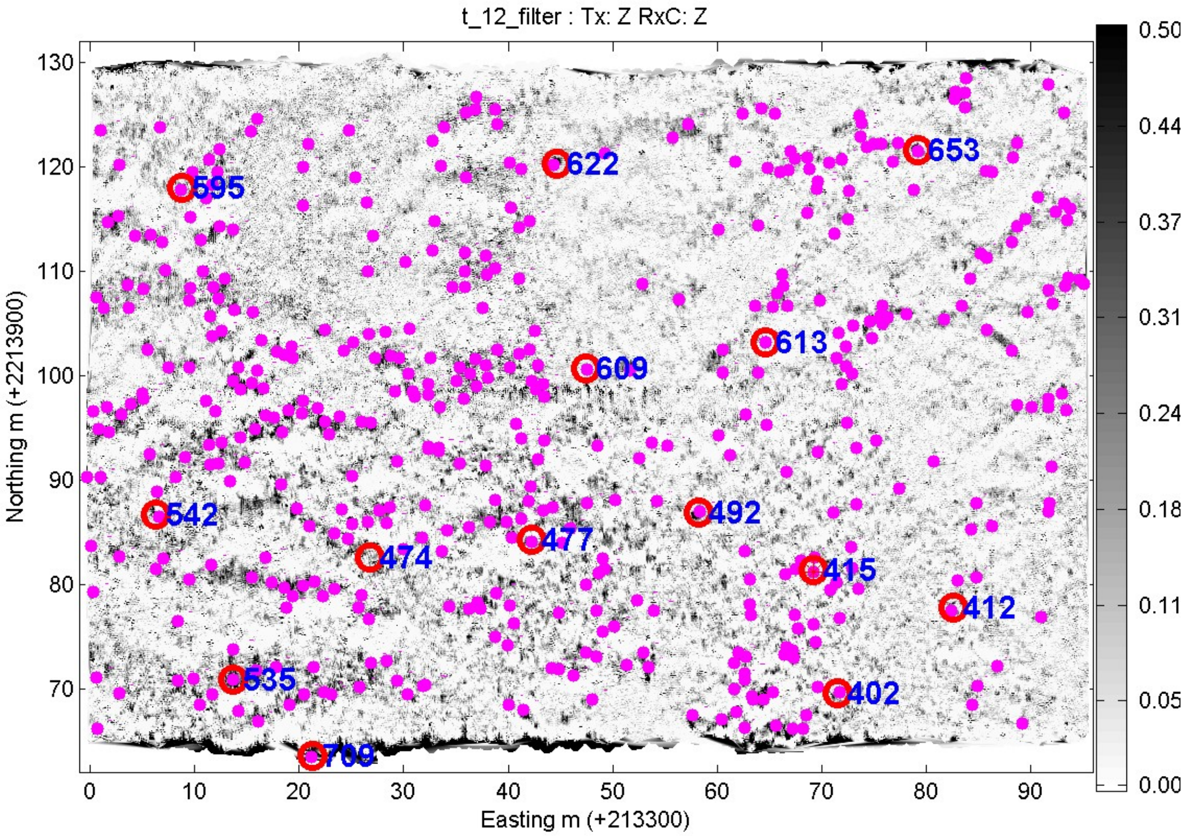


Figure 13: Detection map and location of all selected anomalies and TOI.
The detection map shows the Z-component data for the filtered 1.66 msec time channel. Selected anomalies are indicted with magenta dots. TOI are indicated with a red circle and a label.

All but one seed item were detected. The missed item was a 60 mm mortar buried at 0.4 m depth and labeled WK-474. As shown on Figure 13 (local coordinates: 27 m and 83 m), no anomaly was selected nearby, whereas all other TOI were selected (as indicated with a magenta dot inside each red circle). The data surrounding the missed anomaly is shown in greater detail in Figure 14. The detection data shows a ridge of higher background value traversing the missed anomaly location. The soil-insensitive receivers show no anomalous signal. The 60 mm mortar is completely invisible in the dynamic data. No cued data was collected at that location.

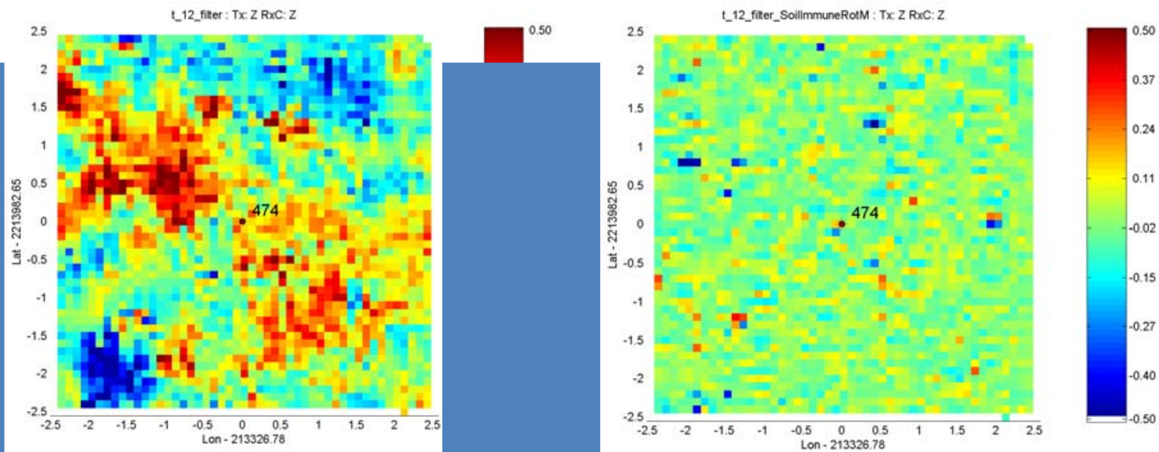


Figure 14: Detection data associated with missed TOI with label WK-474.
Left: View of the gridded detection channel around the missed TOI. Right: View of the soil-insensitive data, which would reveal any anomaly that does not exhibit the typical behavior of magnetic soil.

7.3 CLASSIFICATION WITH CUED DATA

Correct classification relies on the capability to recover accurate target parameters. From the data collection aspect, this requires accurate positioning of the sensor of the picked anomaly of interest. From the data analysis aspect, key parameters include the location, depth and amplitude of the polarizability tensor components.

7.3.1 Anomaly location and reacquisition

The MPV2 cued interrogation started at each anomaly by taking the first measurement at the picked anomaly location. The difference between the picked anomaly location and the first sensor location is shown in the top left panel of Figure 15. The first measurement was located within 0.2 m of the pick 99% of the time, and always within 0.4 m. Given the 5-point interrogation procedure, all pick locations were well contained within the cued interrogation. The top right pattern relates to the accuracy of the pick location and the ground truth documentation. The two locations remain within 0.4 m 98% of the time and within 0.6 m all the time; there again the 5-point interrogation procedure sufficiently extends the survey footprint to ensure that the anomaly is covered.

The same analysis is presented in the lower panels for the MPV3D anomalies, which are a subset of the standard MPV2 anomalies. The graphs show that each anomaly was approached within 0.2 m (lower right panel). There were anomalies for which the distance between the picked location and the documented intrusive result exceeded 0.4 m, which could have caused issues given the smaller footprint of the 3D system. However, inversion of the data on the spot was able to resolve these large offsets and guide the operator to a better location where classification was successful. This occurred for 20% of the anomalies (19 recollects for 119 picked anomalies; 10 recollects for the 53 anomalies for which intrusive results were available).

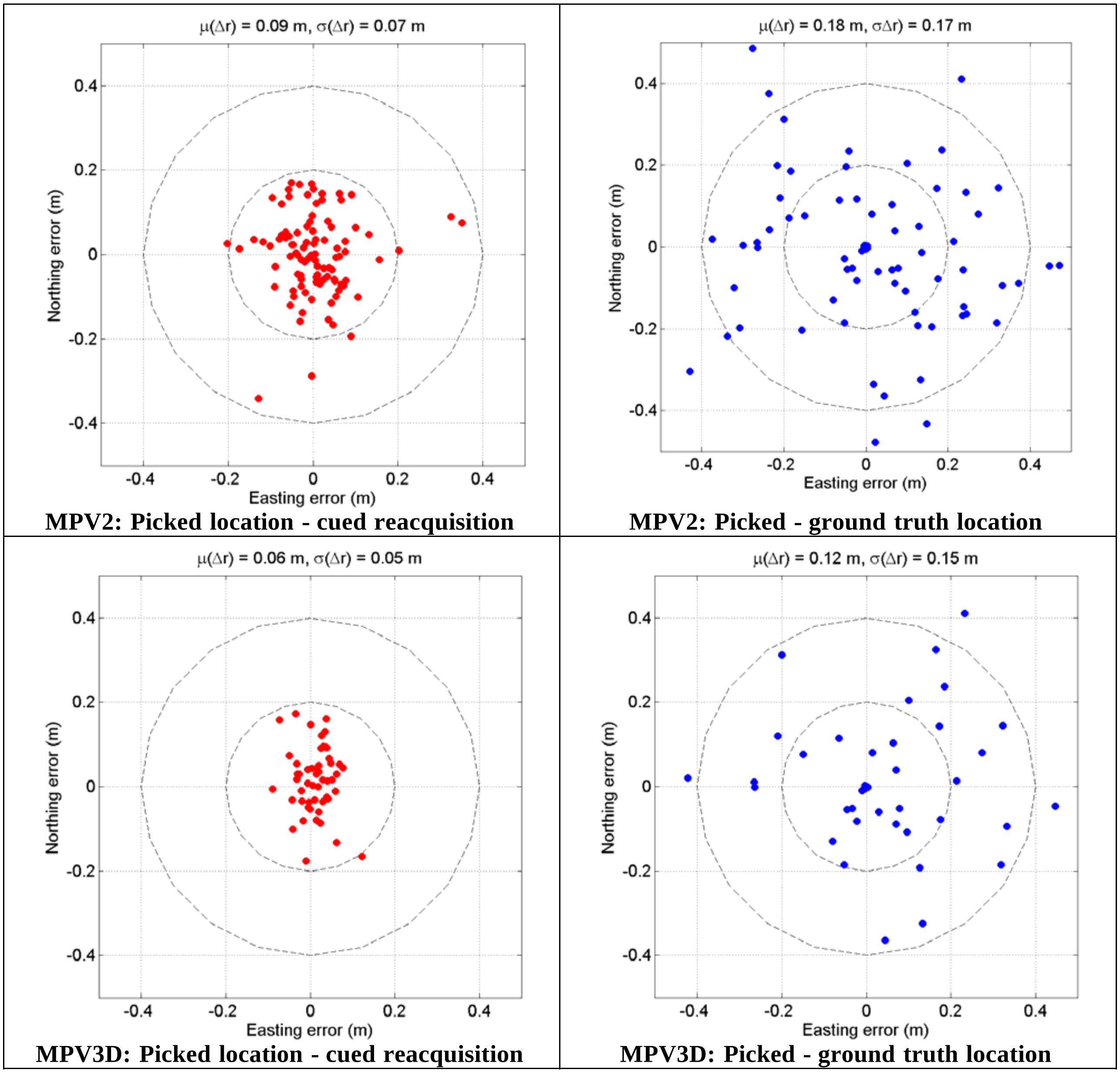
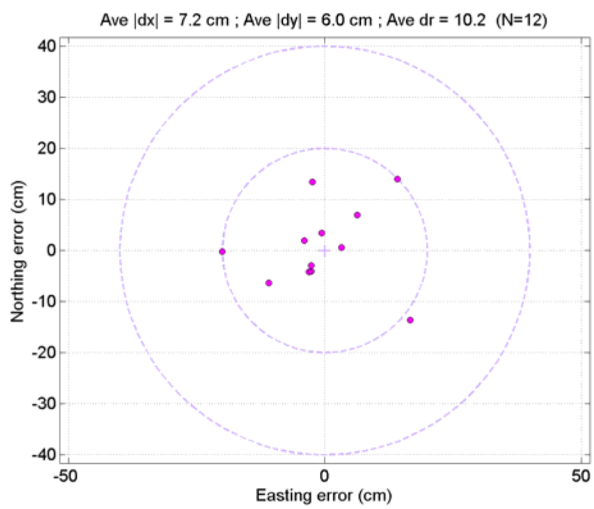


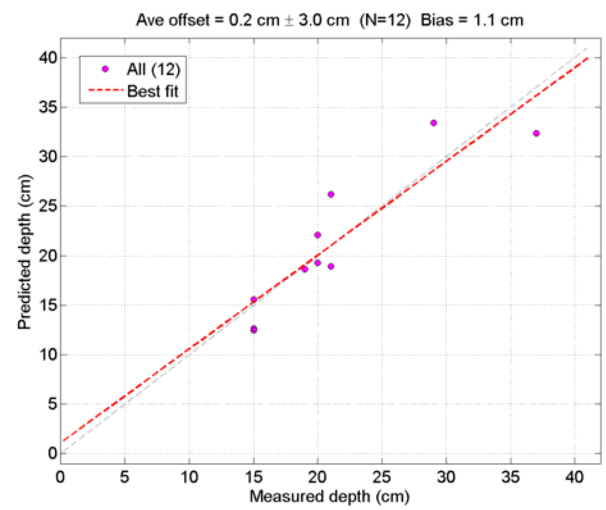
Figure 15: Picked location, cued reacquisition and intrusive result.

7.3.2 Inverted location and depth

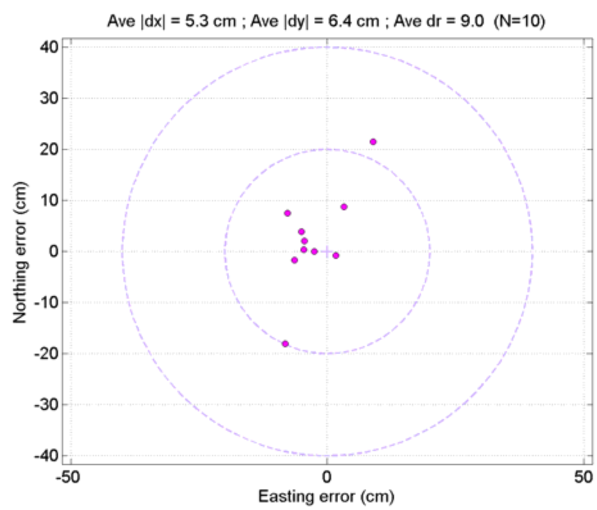
The difference between the inversion-based prediction of the target location and depth and the excavation records of the TOI is summarized in Figure 16. For the MPV2 analysis, one outlier for position corresponds to 81 mm projectile WK-477, a large item for which the definition of location may be ambiguous both for the modeling and ground truth; the second outlier for position is a medium ISO with perfect match to polarizabilities and depth (WK-622); the third outlier for position is 37 mm projectile WK-402 at a depth of 0.30 m with good match to polarizability curves. The depth is always matched within 0.05 m (the objective is 0.10 m).



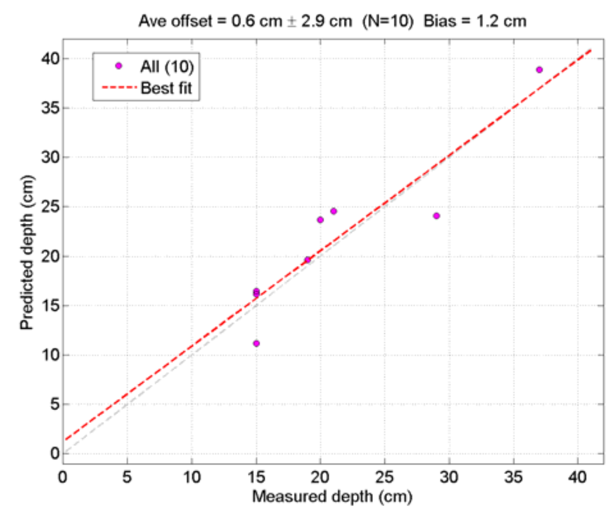
Location error for MPV2-5-point study



Depth error for MPV2-5-point study



Location error for MPV-3D study



Depth error for MPV-3D study

Figure 16: Difference between inversion-based and intrusively-recovered location and depth.

For the MPV3D study, the location outliers are targets WK-402 (0.23 cm) and WK-477 (0.20 m), both of which are position outliers for the MPV2. The recovered locations are within 0.10 m between the two sensors, which may suggest inaccuracy in the ground truth for these two targets. The offset for target WK-622 is only 0.03 m.

7.3.3 Performance measured by ROC curves

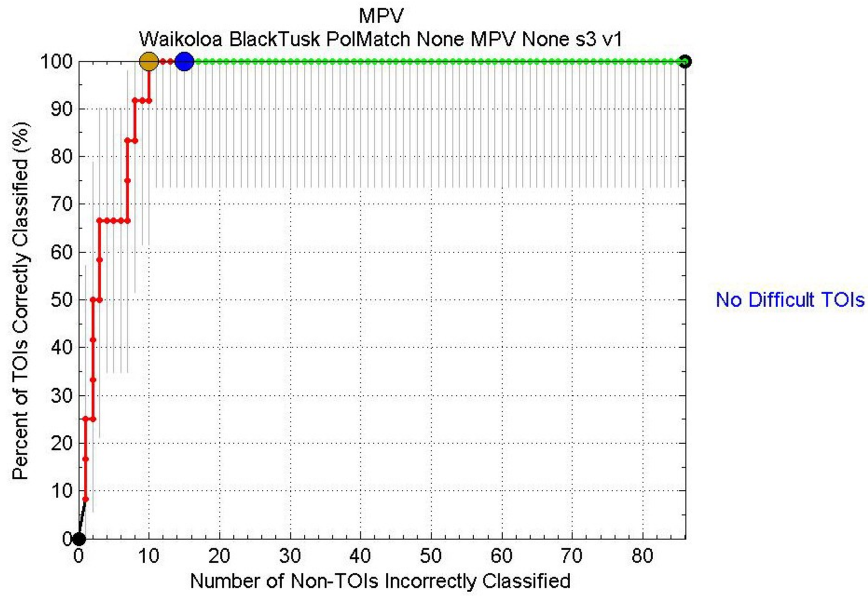


Figure 17: ROC curve for the classification study based on standard MPV2 data. The analyst-defined stop dig point is indicated with a blue dot. The last TOI is indicated with an orange dot.

The Receiver Operator Characteristic (ROC) curves illustrate the performance of the classification process for the MPV2 (Figure 17) and MPV3D studies (Figure 18). In both cases all TOI were found well before the stop dig point. The MPV2 study included 12 TOI and 86 pieces of clutter while the MPV3D had 10 TOI and 43 pieces of clutter.

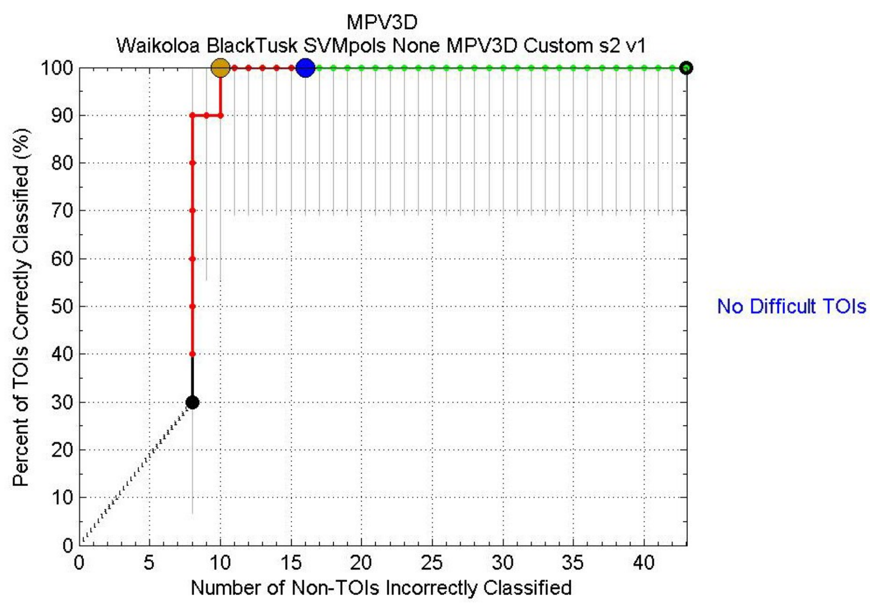


Figure 18: ROC curve for the classification study based on the MPV3D data.

7.3.4 Comparison of polarizabilities with 5-point and 3D measurements

Though classification was successful and efficient with both cued survey configurations, there were cases where the 3D setup might be better suited for recovering polarizabilities. Targets WK-415 and 402 were challenging for classification based on the 5-point data, as shown in Figure 19 (panels A and B). For target WK-415 the 3D configuration clearly recovers the correct target polarizabilities, whereas the 5 point fails to do, likely due to difficulties in establishing a suitable background compensation. The deeply buried WK-402 poses challenges to both setups: the 3D predicts a UXO-like target that should be dug although the size is underestimated; in contrast with 5 points the primary polarizability helps establish the target size although the secondary polarizabilities cannot be reliably retrieved.

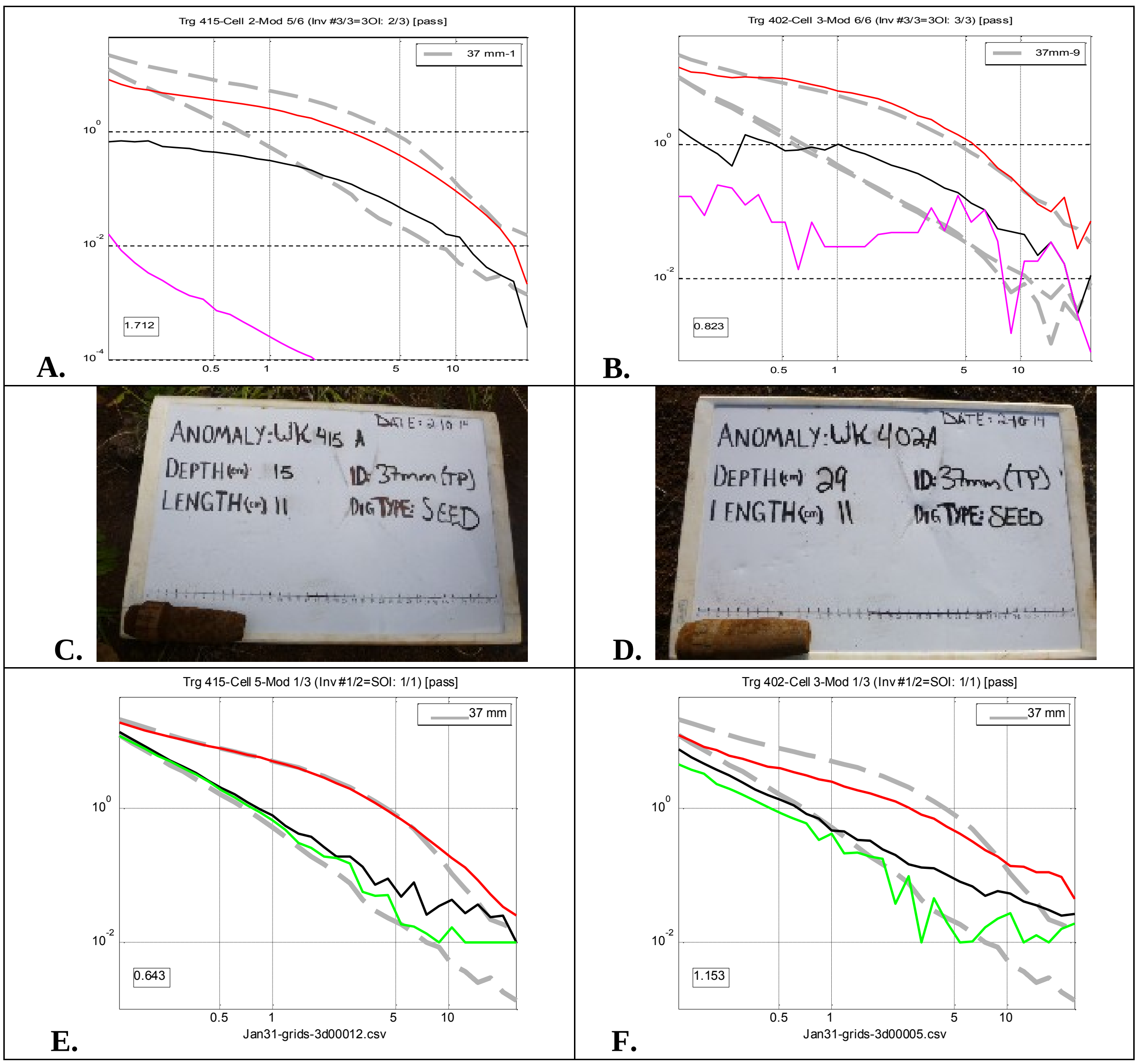


Figure 19: Polarizabilities for 5-point and 3D surveys for two challenging anomalies. Predicted polarizabilities are shown in panels A and B for the 5-point and E and F for the 3D configuration. The ground truth information is shown in panels C and D. Panels A, C and E pertain to target WK-415 and B, D and F to WK-402.

7.4 FIELD PRODUCTIVITY

7.4.1 Detection survey

The detection survey covered 1.5 acres, with survey lines at 0.5-m spacing. Survey ropes were laid on the ground at 1-m spacing for guidance. The detection survey spread over three days instead of two because of afternoon thunderstorms. The time of acquisition of the detection data is shown in Figure **20**. There is a total of 13 hours of effective detection survey for the 1.5 acre site, which corresponds to approximately 0.11 acre per hour, discounting for setup and IVS time.

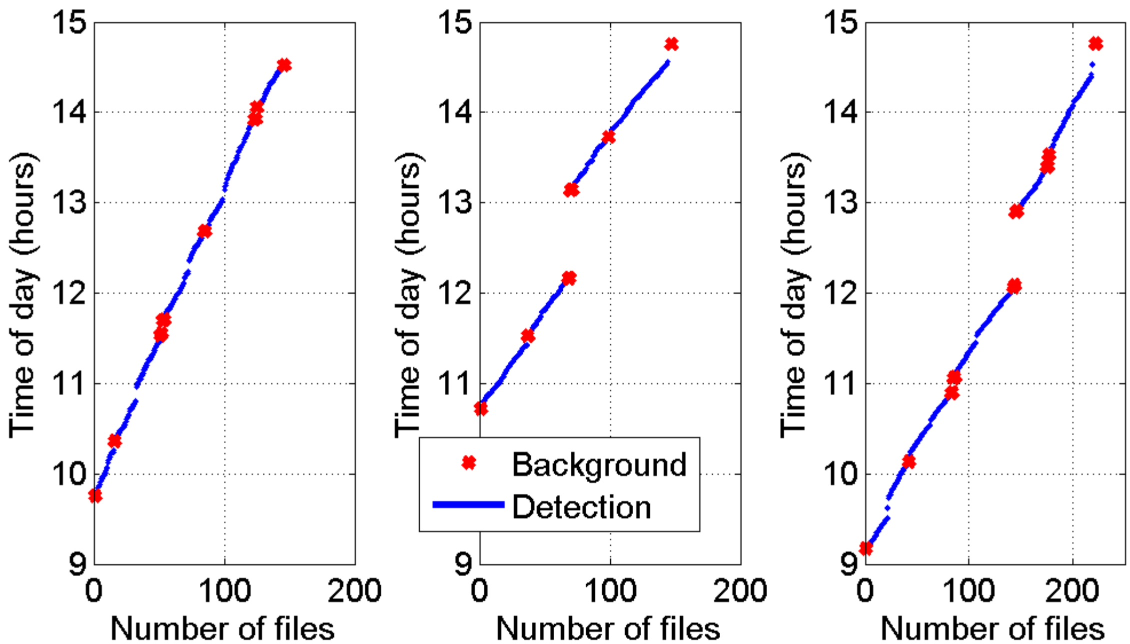


Figure 20**: Time of acquisition of dynamic data collection files (January 21, 23 and 24 2014).**

7.4.2 Cued interrogation

Cued interrogation with the MPV2 in standard 5-point operation was performed over 458 anomalies. The study took place over 5 days, including weather interruptions (Figure 21). There were 17 hours of effective data collection, which translates to 27 anomalies per hour, including recollects. In past demonstrations that rate was closer to 17 anomalies per hour. This improvement relative to previous demonstration is due to the omission of the beacon positioning system, which generally adds set-up time and was not needed here owing to open sky conditions that guaranteed high quality GPS coverage. Note that productivity was lower on the first day because a background measurement was acquired for every anomaly in order to help characterize the background variability. The rate of background sampling was lowered to one in six for the subsequent days.

The MPV3D data collection took place on January 31 2014 right after the completion of the 5-point survey. A total of 120 anomalies were interrogated over the course of 3.5 hours, which amounts to 34 anomalies per hour. Only 140 cued measurements were needed. This was done under ideal conditions with low recollect rate due to accurate pick locations and isolated, single source anomalies that generally required a single sounding for characterization.

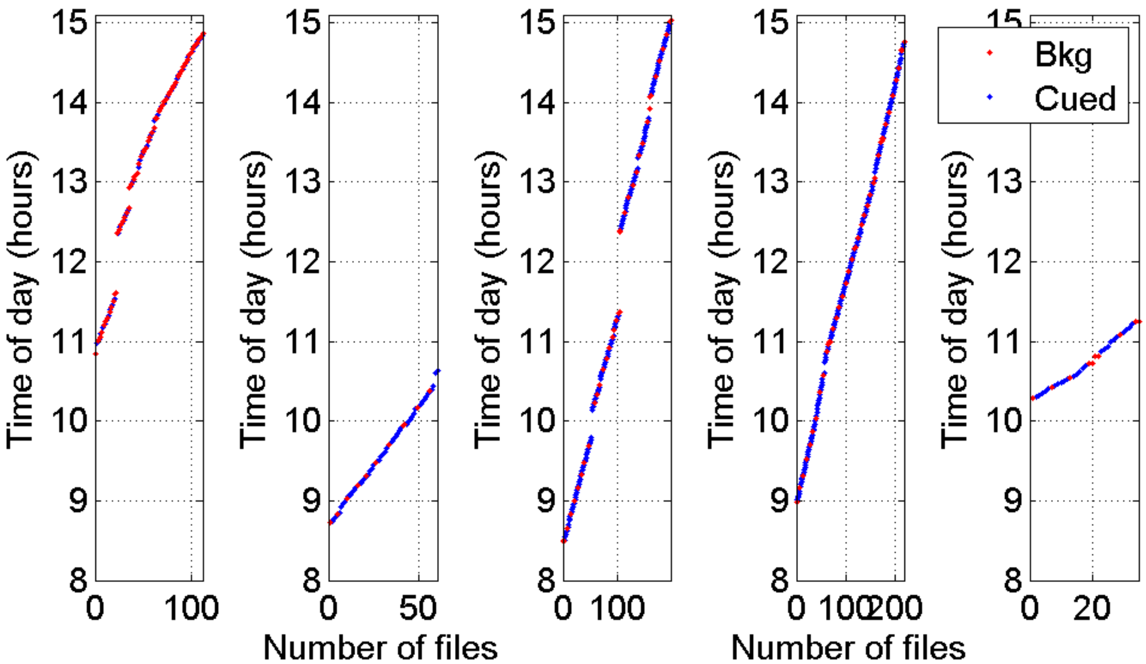


Figure 21: Time of acquisition of 5-point cued interrogation files (January 27, 28, 29, 30 and 31 2014).

8.0 COST ASSESSMENT

Time and resources were tracked for each task to assess the cost of deploying the technology at future live sites. A cost model is proposed in Table 4, assuming an hourly rate of $100. The field activities occurred over two weeks and included one day of instrument setup, 3 days of field testing with updated software and new sensor components, 3 days of dynamic survey and 5 days of cued collection. The mobilization costs were reduced thanks to use of local personnel; only 2 people had to be flown and accommodated. We assume $1000 per plane ticket, a combined per diem and lodging rate of $300 per day and $1000 per week for rental of a pickup truck. We further assume that 3 people were required on the site and do not include SUXO personnel or escort.

Table 4: Cost model for the MPV demonstration.

Cost Element	Data to be Tracked	Unit	Total Hours	Total Cost
Survey preparation and set up				**$36,400**
Sensor maintenance	Unit: $ Cost • MPV maintenance			$5,000
Planning	Personnel: Geophysicist • Demonstration plan and coordination		80 h	$8,000
Development time	Personnel required: Geophysicist Time to test target picking algorithms in the presence of magnetic soil		40 h	$4,000
Mobilization and demobilization	Cost to mobilize to site: 2 people • Flight, hotel, per diem and time • Shipping	8 h 2 h	32 h 4 h	$5,800 $3,200
Instrument setup	Typical field crew: Geophysicist + 2 technicians • First day: assemble, set up and test pit • Last day: packing	8 h 4 h	24 h 8 h	$2,400 $800
Pre-survey testing	Personnel: Geophysicist and electrical engineer on site and one geophysicist off site • Function tests on all technology components (hardware and software) and test field procedures	8 h	72 h	$7,200
Field survey: Daily tasks (8 days)				**$15,500**
Rentals, materials and miscellaneous	Survey equipment rental (GPS) • Material supplies • Travel to site, car rental and gas (x 3 people) • Hotel and per diem (x 2)	1 h $300	2 h 24 h	$2,500 $500 $4,500 $4,800
Instrument verification	Field crew: Geophysicist + 2 technicians • Typical day (GPS set up and IVS surveys) • Analyze IVS data (Geophysicist)	1 h 1 h	24 h 8 h	$2,400 $800
Field survey: Detection (1.5 acre - 3 days)				**$10,700**
Data collection for detection	Field personnel: Field crew of 3 • Collect & record data • Preparation and interruptions	10 h	45 h 18 h	$6,300

Detection processing	Personnel: Geophysicist • Data extraction and QC • Built detection map, establish threshold and pick anomalies • Prepare data for delivery		16 h 20 h 8 h	$1,600 $2,000 $800
Field survey: Cued interrogation (450 anomalies)				**$12,900**
Data collection for cued survey	Personnel: Geophysicist and field crews • Data collection • Normal interruptions • Contingencies (weather)	2.2 min 1 h/d 8 h	51 h 15 h 24 h	$5,100 $1,500 $2,400
Pre-processing and QC	Personnel required: Geophysicist • Import and QC (per flag) • Prepare recollects • Prepare data for delivery	2 min	15 h 8 h 16 h	$1,500 $800 $1,600
Classification of cued interrogation data (450 anomalies)				**$6,800**
Data extraction	Personnel: Geophysicist Extract and analyze cued data	2 min	16 h	$1,600
Parameter extraction	Personnel: Geophysicist Inversion setup & QC	2 min	16 h	$1,600
Classifier training	Personnel: Geophysicist in training Identify features and potential TOI	1.5 min	12 h	$1,200
Classification and dig list	Personnel: Geophysicist in training + expert Test classifier, prepare dig lists and assimilate groundtruth	3 min	24 h	$2,400
COST SUMMARY				
Dynamic data collection per acre (incl. IVS and QC)				**$6,000**
Detection analysis per acre				**$1,300**
Cued data acquisition per anomaly (incl. 3 days IVS and QC)				**$22**
Cued data classification per anomaly				**$15**

9.0 MANAGEMENT AND STAFFING

A flow chart showing the managerial hierarchy and the relationship between the principal investigator (PI) and other personnel is shown in Figure 22.

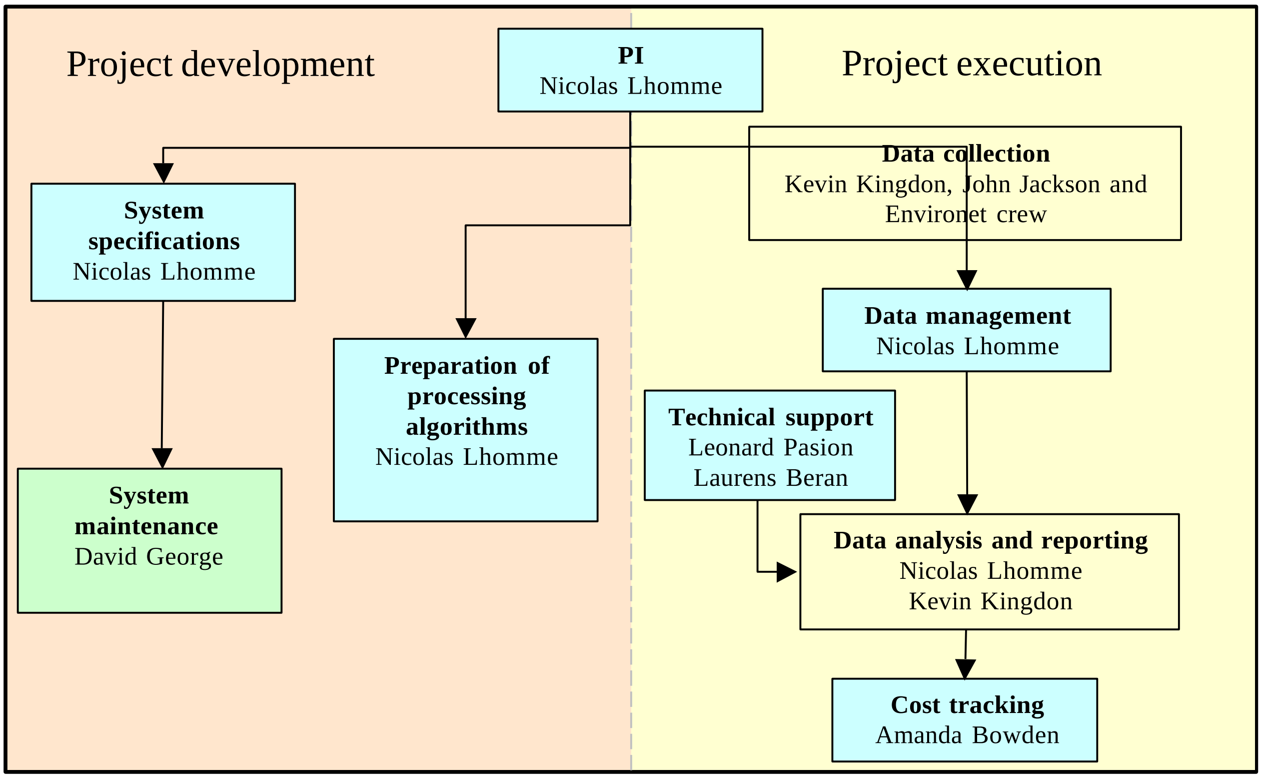


Figure 22: Project management structure for the Waikoloa demonstration.

The Waikoloa study was jointly lead by Kevin Kingdon (Field Geophysicist, Black Tusk Geophysics) and Nicolas Lhomme (PI, Black Tusk Geophysics). The Field Geophysicist went to Grand Junction to test the MPV with David George of G&G Sciences in preparation for the demonstration, then lead the data collection on the Waikoloa site, trained the field crews from Environet and John Jackson (USACE Sacramento) to operate the technology and took part in the data collection for detection and cued interrogation. After the deployment he applied classification to the MPV2 data collected in 5-point cued mode. The PI advised on survey procedures and system specifications and performed most data analysis and data management tasks: daily data QC of the IVS, dynamic and cued data, processing of the dynamic data and anomaly picking, data packaging for distribution, processing of all cued data, classification of the MPV-3D data, retrospective performance analysis and reporting. Laurens Beran and Len Pasion of Black Tusk Geophysics provided technical support in establishing detection thresholds and identifying potential targets in magnetic soils.

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APPENDICES

APPENDIX A: POINTS OF CONTACT

Points of contact (POCs) involved in the demonstration and their contact information are presented in Table 5.

Table 5: Points of Contact for the MPV Demonstration.

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Dr. Nicolas Lhomme	Black Tusk Geophysics 401-1755, W Broadway Vancouver, BC V6J 4S5, Canada	Tel: 604-428-3382 Nicolas.Lhomme@btgeophysics.com	Project PI
Kevin Kingdon	Black Tusk Geophysics 401-1755, W Broadway Vancouver, BC V6J 4S5, Canada	Tel: 604-428-3380 Kevin.Kingdon@btgeophysics.com	Project field Geophysicist
David George	G&G Sciences, Inc. 873 23 Rd Grand Junction, CO 81505	Tel: 970-263-9714 dgeorge@ggsciences.com	Sensor manufacturing and support
John Jackson	US Army Corps of Engineers Sacramento	Tel: John.M.Jackson@usace.army.mil	Geophysicist
Dr. Herb Nelson	ESTCP Program Office 901 North Stuart Street, Suite 303 Arlington, VA 22203-1821	Tel: 571-372-6400 Herbert.Nelson@osd.mil	ESTCP MR Program Manager

APPENDIX B: DETECTION MEMORANDUM FOR THE MPV STUDY

The following is a case study for detection with MPV data collected on Grids C11 and D11 that was submitted on January 27 2014.

B.1. SURVEY IN THE PRESENCE OF MAGNETIC SOIL

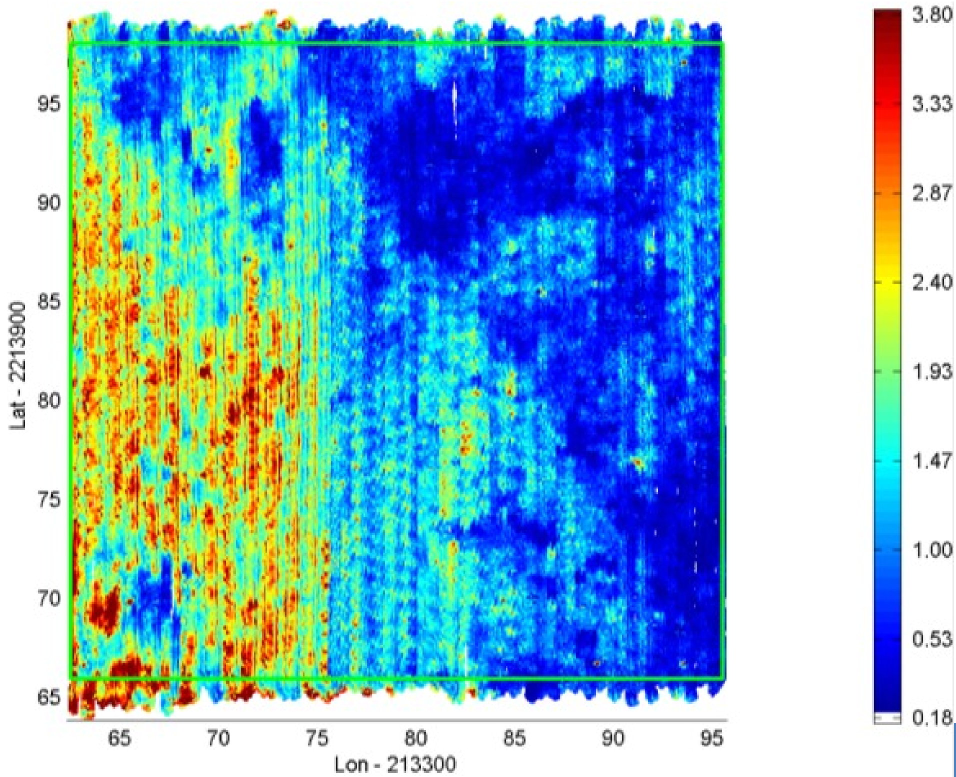


Figure 23: Dynamic data map for grid C11. Raw z-component data for channel 8 (0.8 msec).

The vertical component data are generally used for detection maps because of the strong coupling with objects buried at depth. These data are also strongly coupled with the soil and are therefore particularly sensitive to magnetic soils. Here the raw data suggest that there are areas with strong background response due to the geology.

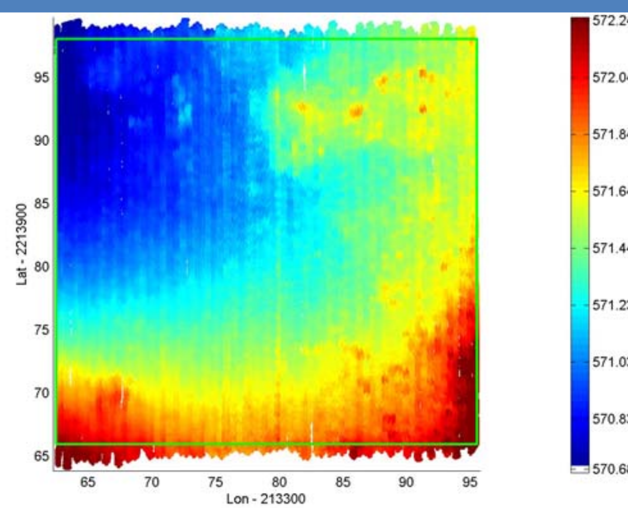


Figure 24: Sensor elevation map. The sensor head tracks the topography by being kept approximately 15 cm-off the ground.

Observations:

- The low amplitude response regions of Figure 23 relate to high elevations in Figure 24. Some of these regions correspond to the "holidays" regions of the original EM61 detection map, where rocky outcrops prevented access with the cart. These areas were mapped with the MPV by raising the sensor higher above the ground, which

decreased the response from the soil.

High background responses are found in the low elevation areas, which have gathered eroded soils. The higher background response is caused by the weathering of the soils, which is known to induce a strong viscous remanent magnetization).

- Stripes in EMI and elevation maps correspond to different sensor clearance heights on each line (different handling of sensor)
- High frequency variations in EMI data are mostly due to variations in sensor clearance (surface roughness and operator motion).

Assuming that the background soil properties smoothly vary of a 5 m distance, we median filter the data to remove most of the background variability at the site (Figure 25).

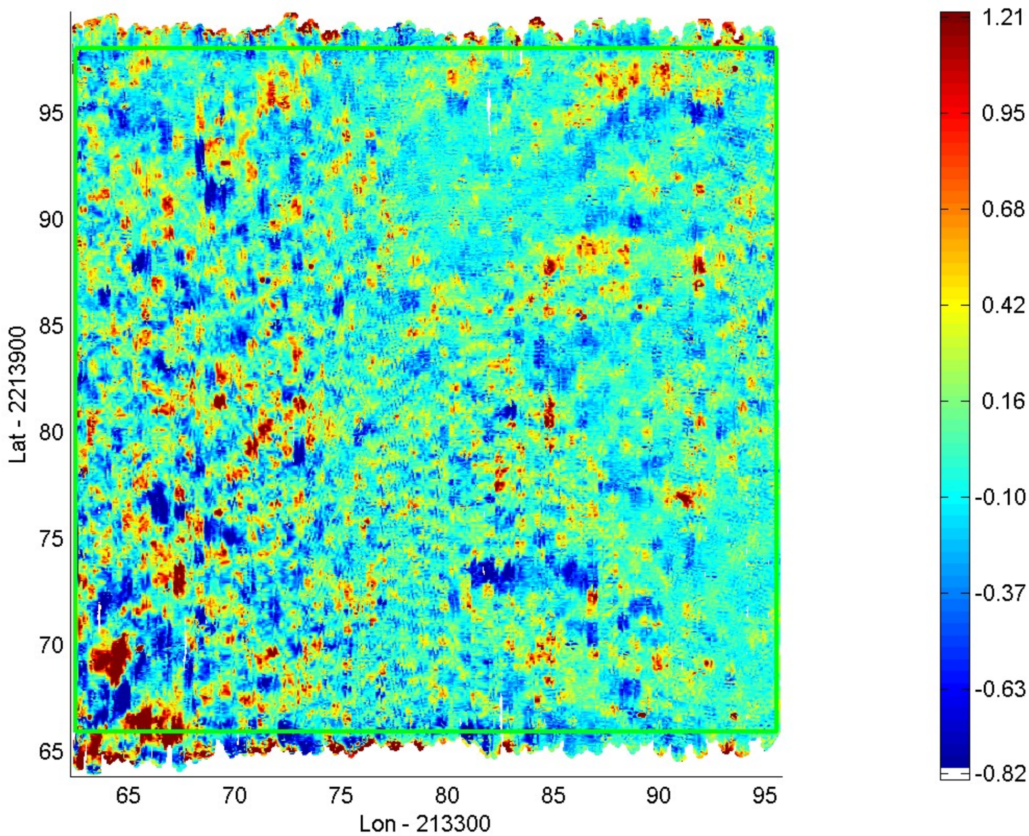


Figure 25: Detection map with filtered z-component data over grid C11.

B.2. DETECTABILITY

The original objective at the site was to find 37 mm projectiles at 30 cm depth. Dynamic and static data were collected on the IVS and over test pits with two types of 37 mm projectiles (M63 and M74) buried in soils in order to test the ability to detect targets and retrieve reliable target parameters.

Analysis of the IVS data shows that large, medium and small ISO are detectable and classifiable a shallow depth. However, the small ISO buried at 27 cm was not detectable.

Analysis of data collected over 37 mm projectiles shows that, in the region near the IVS, targets are barely detectable at 30 cm. Depending on the target orientation, dip and position relative to survey lines, the target response has similar amplitude as the soil response, and therefore the ability to detect will be extremely sensitive to local soil conditions.

Data were also collected at shallower depth to retrieve target parameters. These parameters were used to simulate the target response under the most challenging conditions, identify the best channels for detecting 37 mm in a magnetic soil and define appropriate thresholds.

B.3. GSV ANALYSIS

B.3.1. Channel selection

Soils with viscous remanent magnetization have particular time-decay characteristics. This affects the sensor receivers in a predictable manner, with the strongest effects on the vertical and radial components when the sensor is nearly parallel to the ground. Analysis of the background noise measured on site relative to the response of a 37 mm projectile suggests that the late time channels may be most effective for detecting targets while screening out soil and scrap.

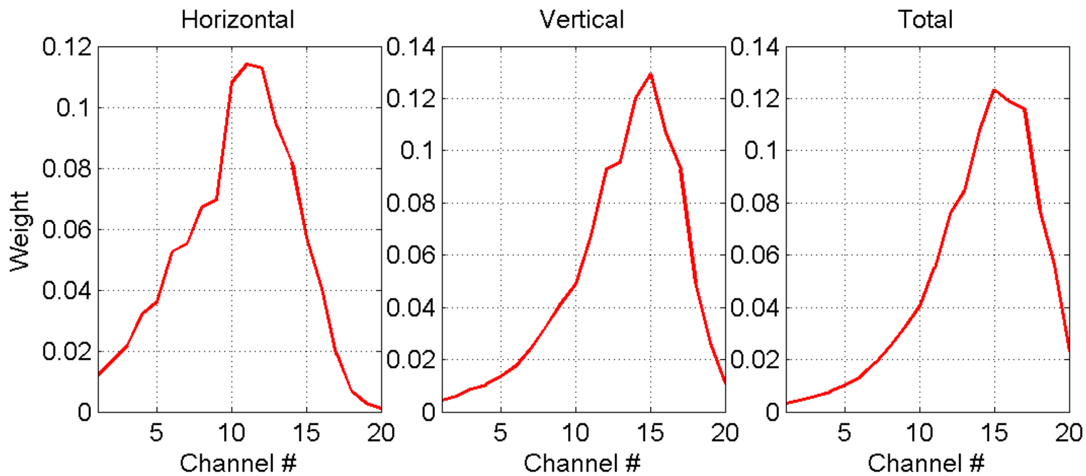


Figure 26: Optimal weighting of MPV sensor channels for detection for the horizontal- and vertical-component data. (Channel 10 corresponds to 1.1 ms and channel 15 to 2.9 ms)

B.3.2. Threshold

The response of a 37 mm projectile in a dynamic survey was simulated to identify the worst case for detection. Each MPV receiver has a different sensitivity due to its position relative to the transmitter; therefore, we propose to apply different thresholds for each receiver (Figure 27 and Figure 28). For a target directly below the sensor head, the weakest coupling between target and receiver occurs when the target is horizontal.

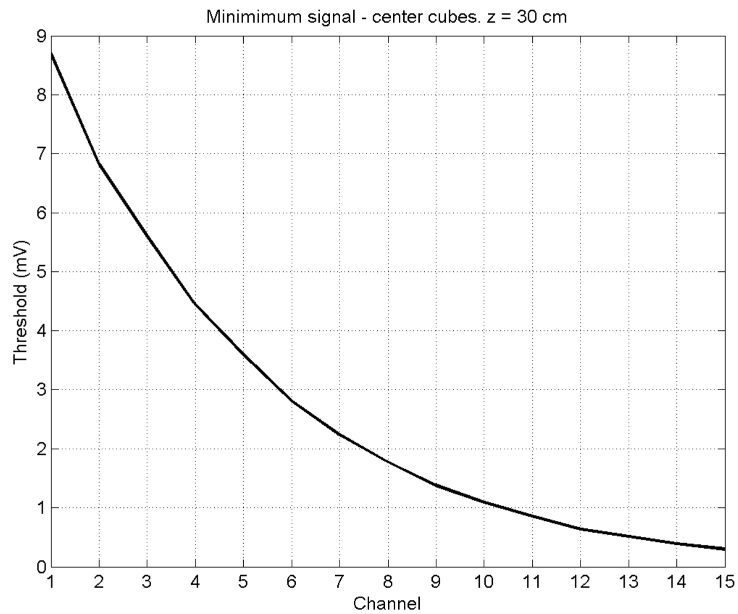


Figure 27: Minimum response of a 37 mm projectile buried at 30 cm depth below MPV center cube.

The detection survey was conducted with 50 cm line spacing. Generally, the tracks of side cubes on two adjacent lines should be separated by approximately 10 cm; therefore, a target would be at the most 5 cm away from a cube. The predicted target response on the side cubes is shown in Figure 28 as a function of the data gap or maximum receiver-target separation for several time channels (the amplitude of the target response for the Z-component data diminishes by a factor 2 over 20 cm).

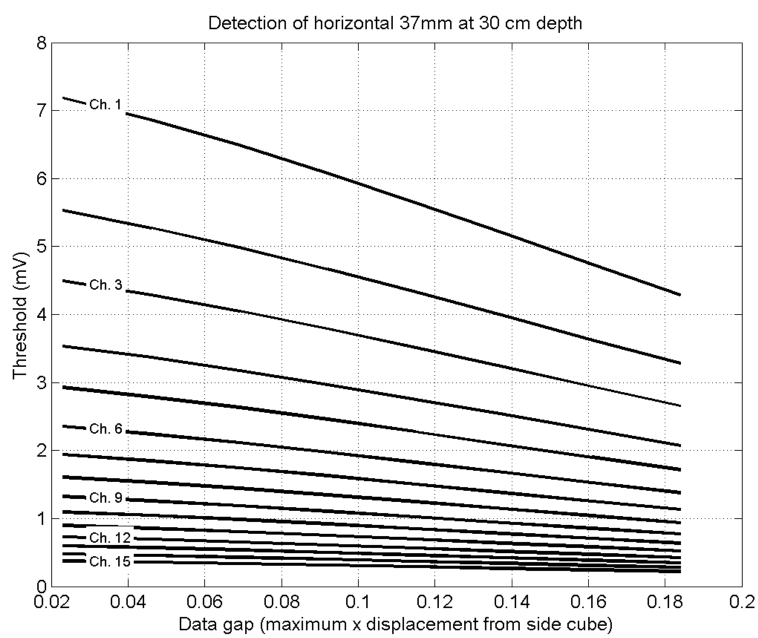


Figure 28: Response on side cube as a function of the distance from the target.

B.4. TARGET PICKING

Targets were automatically selected on a synthetic channel. Vertical-component data for Channels 12 to 14 were median filtered with a 5 m window length. The channels were added by taking a weighted average using the time-gates width. The same procedure was applied to detection thresholds for each of the channels. Targets were first picked along lines, applying a different threshold for center and side receivers. The worst case scenario of 20 cm separation between receiver and target (40 cm gap) was first applied. The low-amplitude detections were re-examined to adjust the threshold as a function of the receiver-target separation. Detected targets were subsequently aggregated by combining picks within a 60 cm radius. The resulting targets constitute the main list illustrated in Figure 29 and Figure 30.

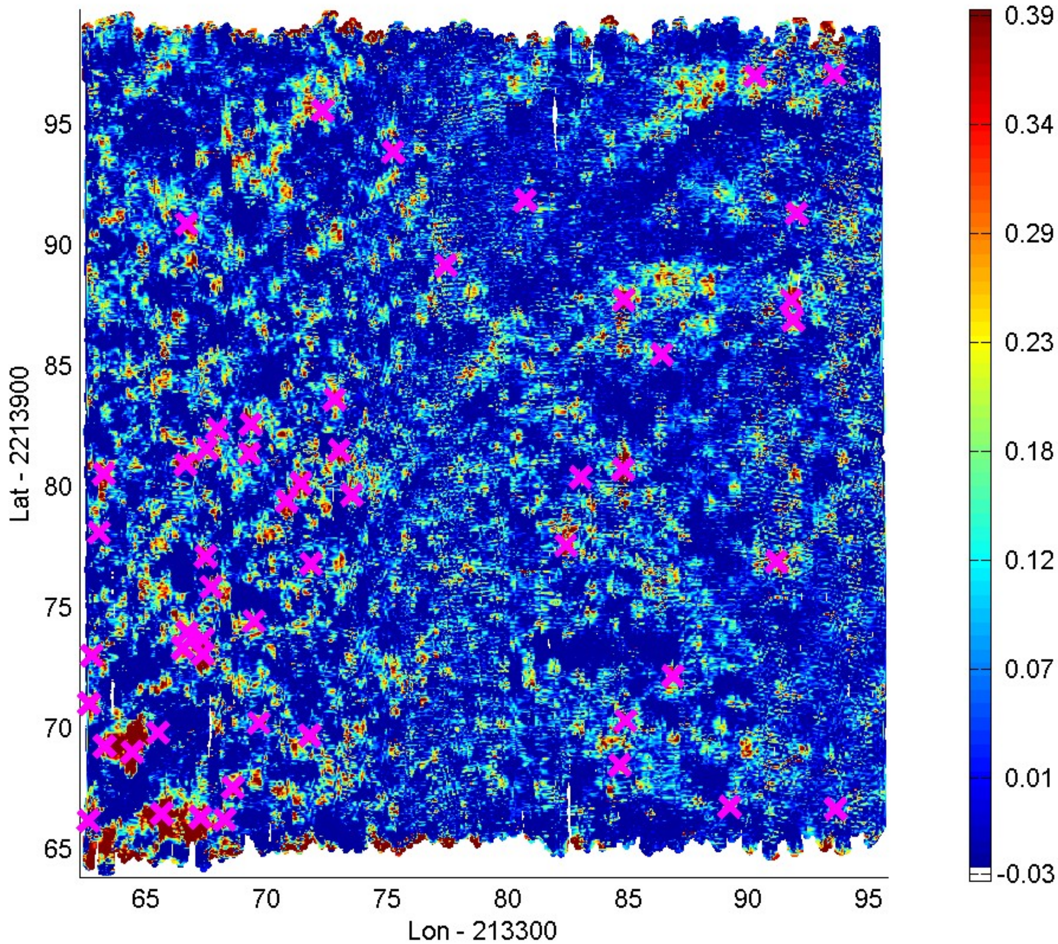


Figure 29: Detection map with 53 picks on Grid C11 (channel 12 filtered).

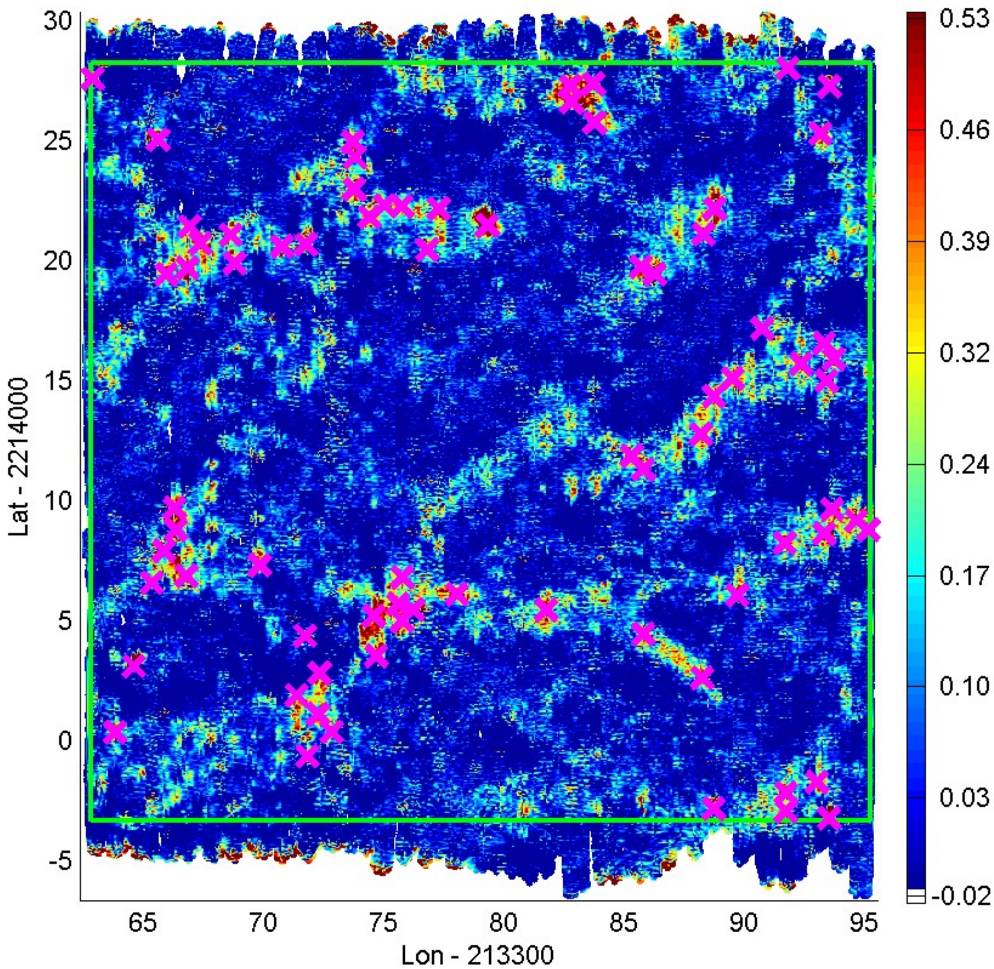


Figure 30: Detection map with 75 picks on Grid D11 (channel 12 filtered).

Transverse components are less sensitive to magnetic soil (across or X-component data on front and back cubes, Y-component data on side cubes). The least soil-sensitive component data were assembled in a composite channel to add a new detection channel. Targets were picked on that channel to supplement the main list (labels 5000 and up). The corresponding picks are shown in Figure 31.

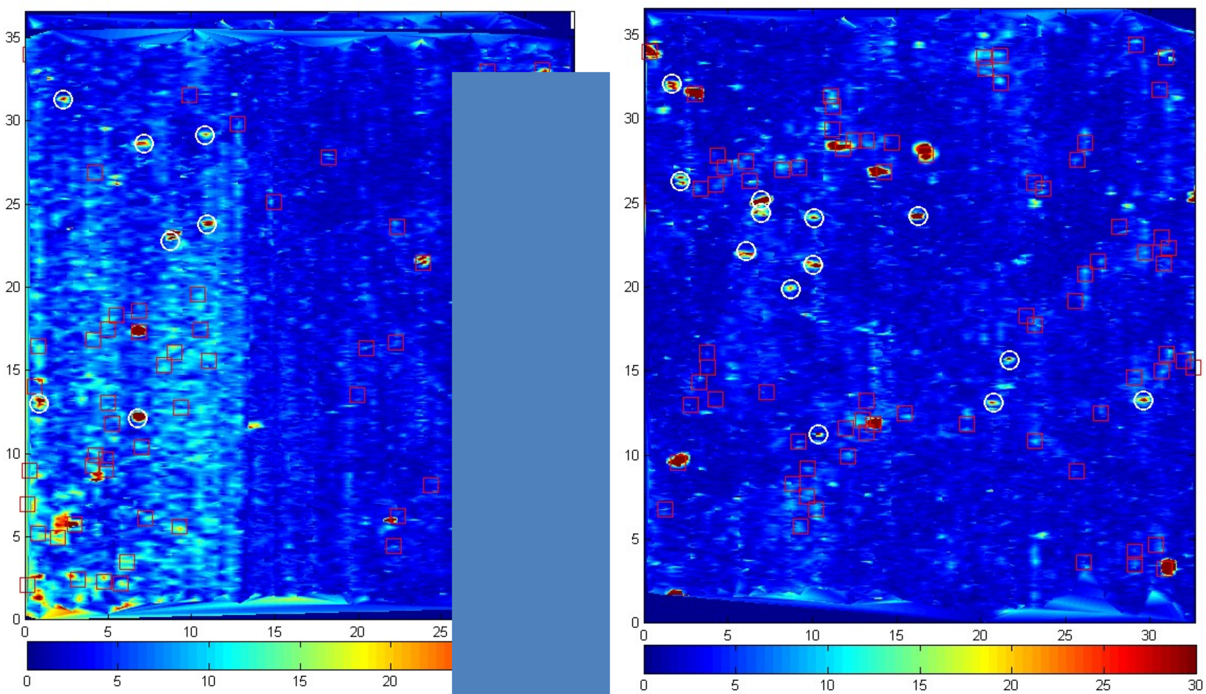


Figure 31: Detection with the least soil-affected components on grid C11 (left) and D11 (right). The red squares are the main targets. The white circles are the added picks.

APPENDIX C: CLASSIFICATION WITH THE STANDARD MPV2 CUED DATA

C.1. WAIKOLOA MPV 5- POINT CUED CLASSIFICATION METHODOLOGY AND RESULTS

The MPV 5 point cued dataset consisted of one, two and three object inversions. Open sky conditions at the site provided reliable RTK positioning to accurately locate the 5 different measurement points centered around the source location determined from the dynamic surveys. Model selection was performed prior to classification. The main focus of the model selection was identifying responses originating from magnetic soil sources, rejecting non-physical models and ensuring that for closely spaced targets, only models corresponding to the intended centered target were passed and models fitting nearby adjacent targets were failed. Although 459 anomalies were interrogated with the MPV using the 5-point configuration, intrusive investigations were only carried out on 98 of those anomalies. It is on that set of 98 MPV 5-point measurements on which the classification described in this section was performed.

C.2. TRAINING DATA SELECTION

A library of reference polarizabilites obtained from data collected at previous sites augmented by test pit measurements of Waikoloa specific TOI was the starting point for training data selection. The *QCZilla* software was used to search for polarizabilities within the dataset that matched the items in the reference library. No matches were found for many of the larger items and these items were therefore removed from the initial reference library to be used at Waikoloa. Because of the limited number of targets in the dataset, rather than making a separate training data request, the s1V1 diglist was submitted with a stop digpoint set at the final item of interest for training data. Note that a much more comprehensive reference library was used in the final S3V1 diglist as a conservative measure. The analyst reviewed inversion results noting models which had characteristic axis-symmetric properties of UXO and cases where recovered polarizabilities matched well with smaller fuze-like items found at Waikoloa (reference polarizabilities obtained via test pit measurements). The first training request (S1V1 diglist) focused on a library containing 7 unique items as shown in table 1.

Target type	Number of variations in library
Medium ISO	1
37mm	1
SCAR fuze	1
Tbar fuze	1
Fuze	1
Fuze-2	1

Table 6: Targets included in the initial S1V1 reference library.

Testpit and IVS measurements had suggested that classification in the presence of the magnetic soils at Waikoloa would be challenging. The IVS included a small ISO which, while detectable at a depth of 30cm, could not be reliably classified. It was observed that secondary polarizabilities were often poorly constrained. For these reasons, the initial training data selected focused on both the targets with high confidence matches to all three polarizabilites for items in

the reference library (i.e. medium ISO) as well as targets that produced polarizabilities that did not have well constrained secondary polarizabilities.

C.3. SELF-SIMILAR POLARIZABILITIES

Having eliminated items from the reference library that do not match any of the recovered polarizabilities in the dataset, we next want to insure that there are no TOI at the site which are outside of the reference library and add any new TOI found to the library. To search for these items, we perform cluster analysis in the size decay feature space, looking for self-similar polarizabilities. This is done using the *TrainZilla* software where the user can draw a polygon in feature space and specify misfit parameters that will be used to look for self-similar polarizabilities within the defined polygon. The full feature space was examined for clusters of self-similar polarizabilities representing new TOI classes but none were identified. This was not unexpected given the limited number of anomalies in the dataset.

C.4. A CHALLENGING CLASSIFICATION PROBLEM

In order to illustrate the difficulties associated with performing classification at the Waikoloa site, it's useful to first consider a relatively large and shallow target. Figure 32 shows the recovered polarizabilities obtained from what the S1V1 ground truth revealed to be a medium ISO at 15cm depth. All three inversions (SOI, 2OI, and 3OI) generate a model with polarizabilities that match well with medium ISO reference polarizabilities (shown as a dashed grey line in Figure 32). This consistency of recovered polarizabilities builds analyst confidence in choosing to dig the target in question as it has a high likelihood of being a TOI.

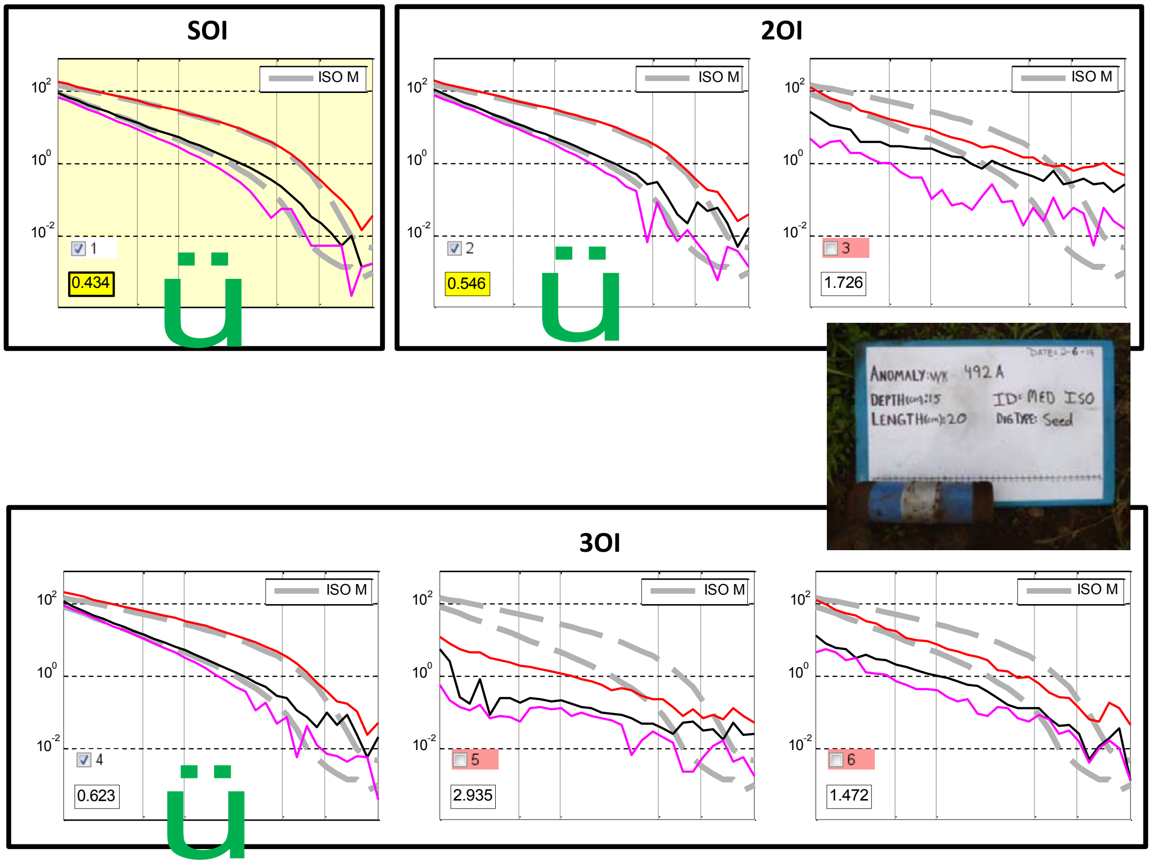


Figure 32: Inversion results for target 492, a medium ISO at 15cm depth. All three inversions produce a set of polarizabilities that match well with the medium ISO reference library item as indicated by green check marks.

The initial ground truth results from the S1V1 diglist also produced results that suggested the classification problem at Waikoloa would be difficult. For example, Figure 33 shows results for a 37mm at a depth of 20cm. While the results for the single object inversion produce a good quality match to a reference library 37mm, the results for both the 2OI and 3OI are not nearly as compelling. While the SOI result is sufficient for successful classification, these results suggest that the classification problem could be relatively difficult at Waikoloa as a 37mm at 20cm depth has not been a particularly challenging target at previous sites.

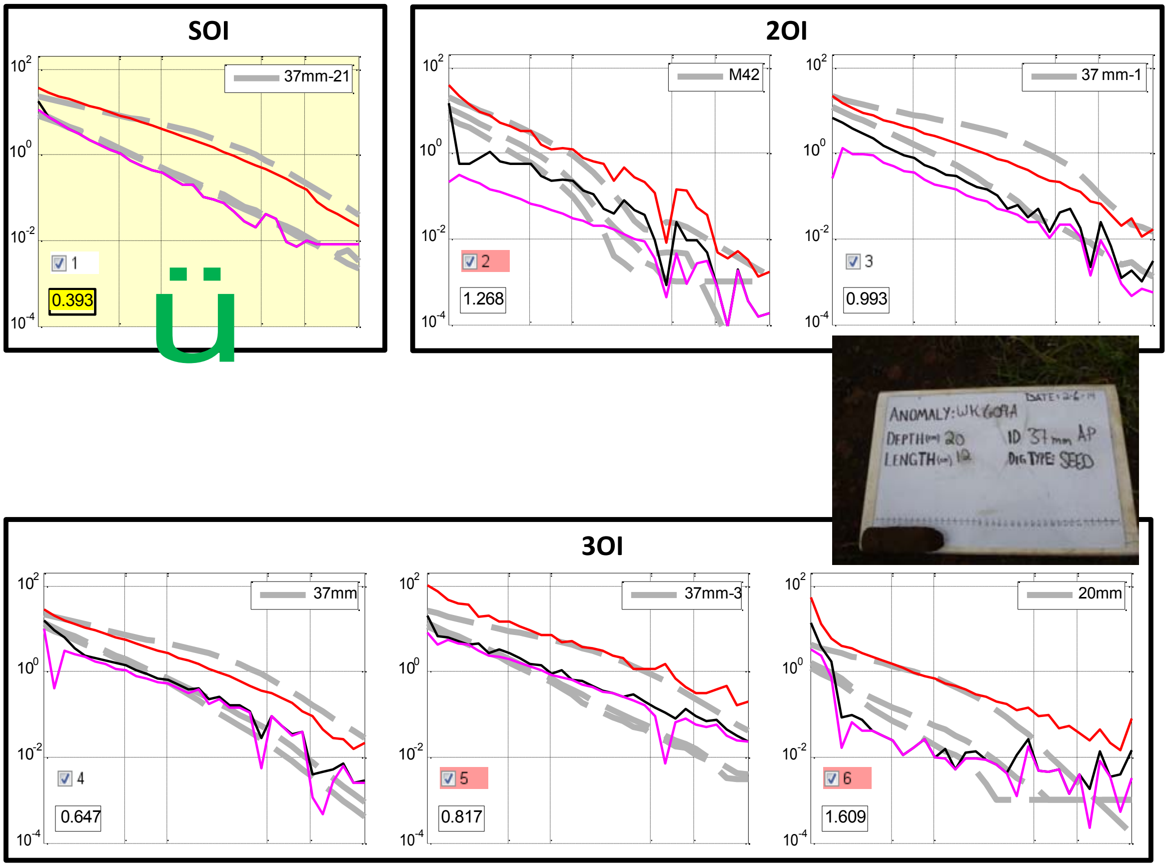


Figure 33: Inversion results for target 609, a 37mm projectile at 20cm depth. Only the single object inversion produces a set of polarizabilities that match well with the 37mm reference library item as indicated by the green check mark.

Ground truth results from the S1V1 diglist also revealed a 37mm projectile at a depth of 29cm (target 402A). Based on the difficulties successfully recovering polarizabilities for a small ISO at 30cm depth in the IVS, it was anticipated that this would be a difficult target to successfully classify. It was selected from training data based on one of the 3 models in the 3OI (see the green check mark in Figure **34**). In that case it is only primary polarizability that produces a match to the 37mm reference as the recovered secondary polarizabilities are not well constrained. Neither the SOI nor either of the models from the 2OI produce polarizabilities that match well with a 37mm reference item.

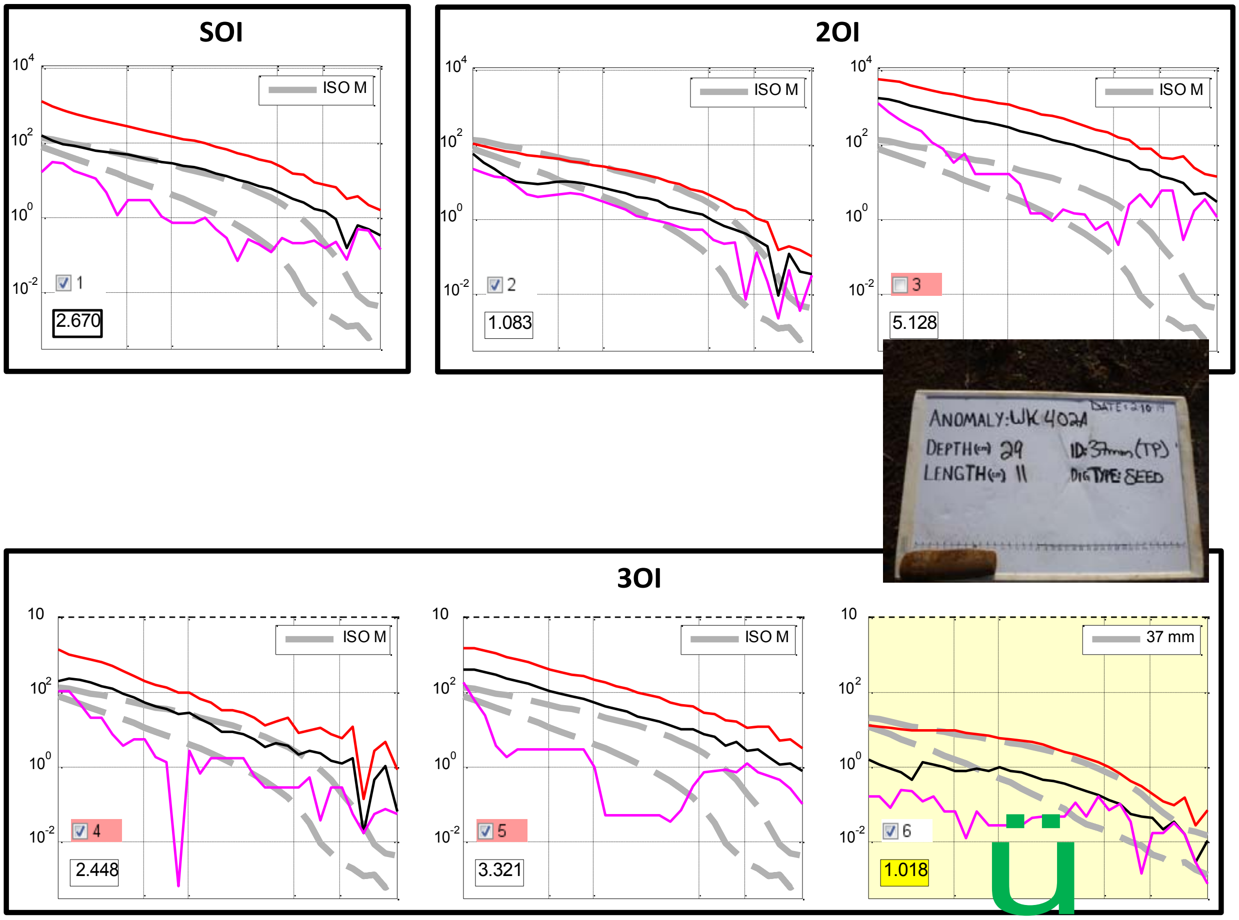


Figure 34**: Inversion results for target 402A, a 37mm projectile at 29cm depth. Only one model of the three object inversion (3OI) produces a primary polarizability that match well with the 37mm reference library item as indicated by the green check mark. Secondary polarizabilites are not well constrained for this deeper target.**

Perhaps the most troubling results from a classification level of difficulty viewpoint were those for target 415A. Ground truth obtained from the S1V1 diglist revealed this target to be a 37mm projectile at 15cm depth. None of the inversion results produce polarizabilities that are a high quality match to a 37mm reference library item and the secondary polarizabilities are not well constrained. This item was chosen for training by the data analyst because of the consistent, slow decaying primary polarizability present in one of the models from each the SOI, 2OI and 3OI that matches the general shape of the 37mm reference polarizability. Often these shifts in recovered polarizability amplitudes relative to the reference library polarizabilities are indicative of the presence of a second source or a potential issue with the background measurement.

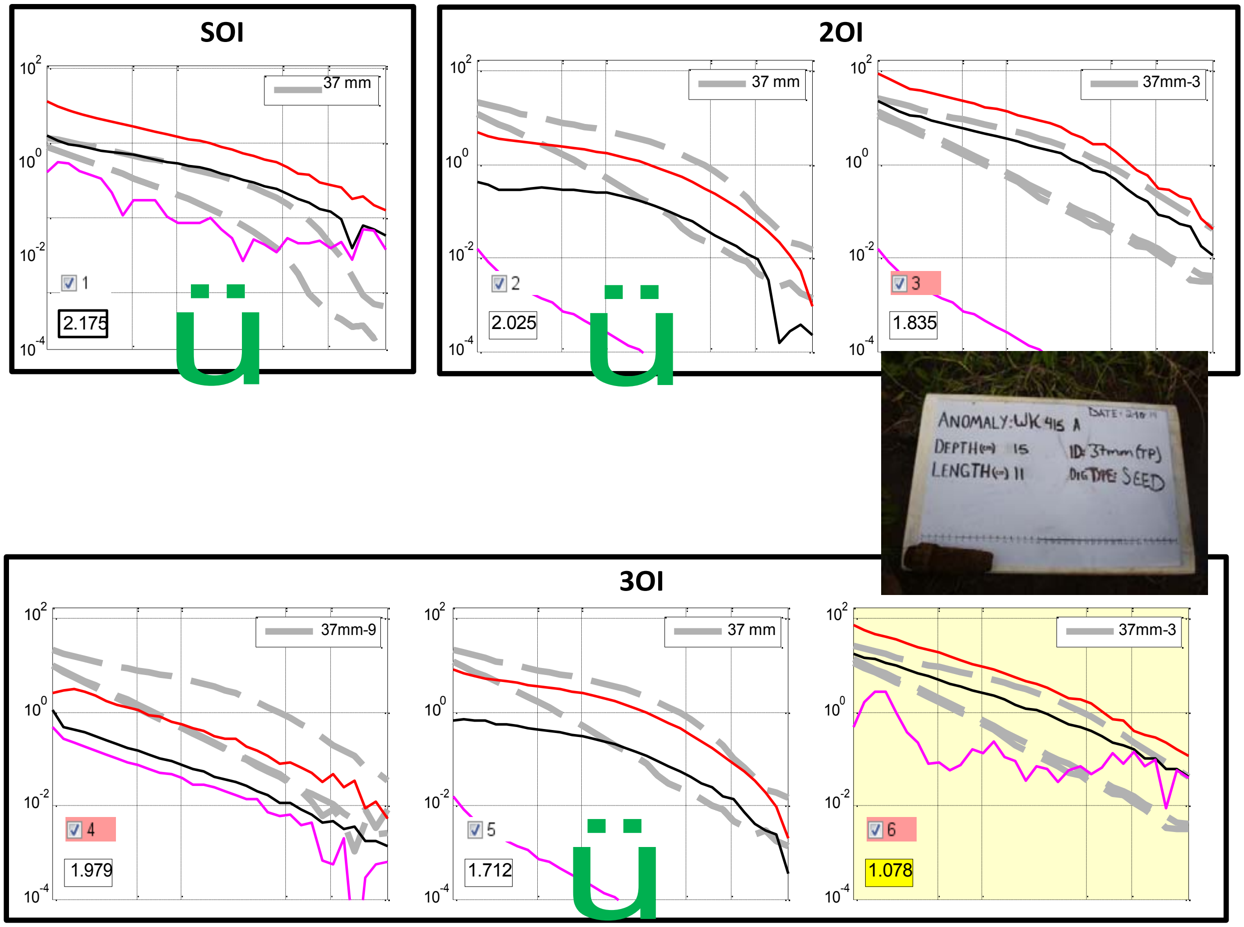


Figure 35: Inversion results for target 415A, a 37mm projectile at 15cm depth. Even though no inversion presented a high quality match to library reference polarizabilities, this item was selected for training because of the slow decaying primary polarizability in a model from each of the SOI, 2OI and 3OI as indicated by the green check marks.

S1V1 groundtruth results suggested that a conservative classification approach was necessary for the Waikoloa site. Based on the S1V1 results, a number of items were added to the reference library including an 81mm mortar (that was initially selected because it matched the shape of a medium ISO reference polarizability with a slightly elevated primary polarizability) as well variants of the 37mm projectile polarizabilities discovered through S1V1 groundtruth (e.g. 37 mm with and without rotating band, etc). A number of non-TOI were also identified in the S1V1 groundtruth including 81mm tail booms, horseshoes, and fuzes. A number of the small fuzes originally in the S1V1 library were found to have no matches to recovered polarizabilities within the entire dataset so they were removed from the reference library producing a S2V1 library as shown in Table 7. The reduction to only 3 target types in the reference library for the S2V1 diglist is a reflection of the very small number (98) of total anomalies in the dataset.

Target type	Number of variations in library
Medium ISO	1
37mm	4
81mm	2

Table 7: Targets included in the S2V1 reference library.

The S2V1 requested 4 additional digs past the stop dig point of the S1V1 diglist. These were scenarios similar to Figure 33 and Figure **34** where only a single model matched a reference polarizability and it was often not a high quality match with secondary polarizabilities being poorly constrained. Three of the four additional S2V1 digs were revealed to be soil responses in ground truth and the fourth item was a survey nail marking the corner point of a grid.

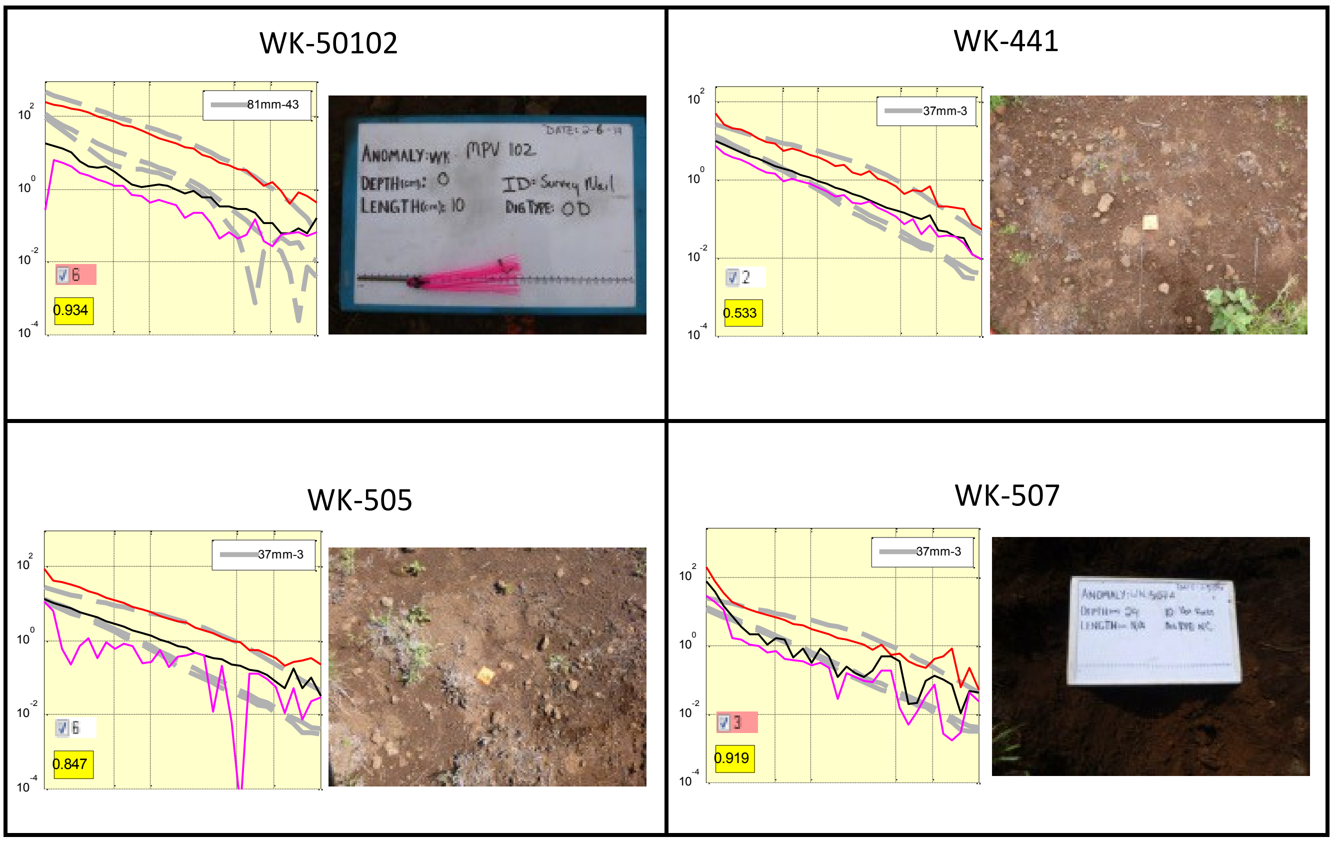


Figure 36: Groundtruth for the four items added to the S2V1 diglist as well as the best fitting recovered polarizabilities to an S2V1 library item.

With no additional TOI discovered in the S2V1 diglist, one final step was taken to expand the reference library to include polarizabilities for a wider range of targets as listed in Table 8. Based on the expanded reference library, one additional target (WK-50117) was added in the S3V1 diglist which was revealed to be another "no contact" intrusive investigation suggesting the response was due to a magnetic soil response. At this point, the recovered polarizabilities for all remaining targets beyond the S3V1 stop dig point were compared with fits to a soil model and

the decision was made to finalize the diglist at the S3V1 stage as the remaining targets were believed to be either due to magnetic soil responses or small, fast decaying targets representing items smaller than the smallest TOI for the site.

Target type	Number of variations in library
Medium ISO	1
37mm	5
81mm	2
105mm	1
60mm	1
20mm	1
40mm	1
BLU26	1
BDU28	1
M42	1
155mm	1

Table 8: Targets included in the S3V1 reference library.

C.5. CONCLUSION

Final scoring for the complete dataset is shown in Figure 17. All TOI for the site were identified in the first 25 digs leading to a 75% reduction in the number of digs. The results indicated that, although classification at Waikoloa is challenging, it has the potential to significantly reduce the number of digs using a conservative approach.

APPENDIX D: SUPPLEMENT MATERIAL FOR THE CLASSIFICATION WITH MPV-3D CUED DATA

This project was the first classification study with 3D-MPV data. Given the novelty and the adverse magnetic soil context, a conservative approach based on standard classification practices was adopted. The analysis process can be illustrated by Figure 37, which shows in individual panels the polarizability decay curves that were retained for each anomaly to generate the dig list. A ground-truth report for the first 30 anomalies of the dig list is presented below.

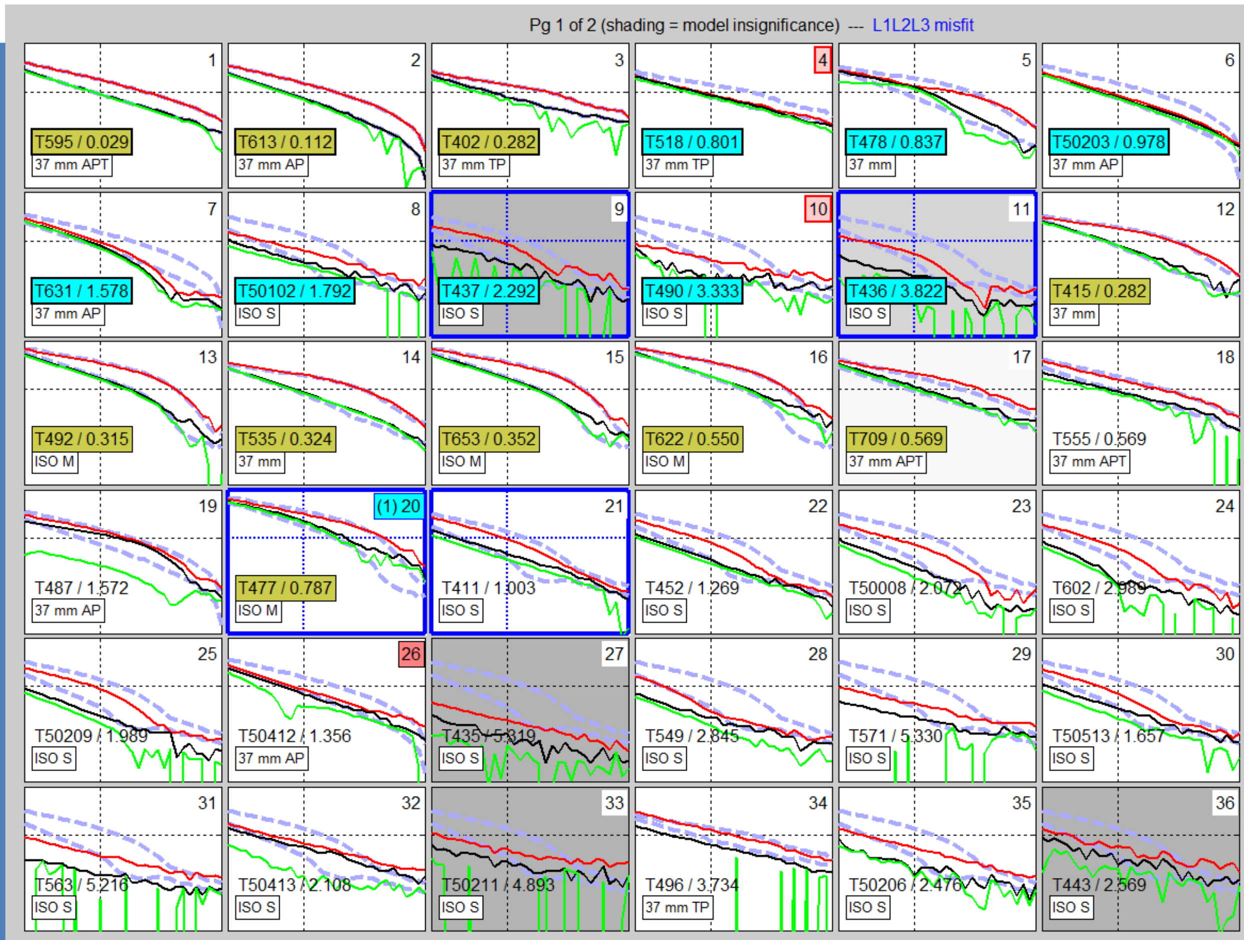


Figure 37: Polarizability decay curves for each anomaly in dig list order for the first 36 items. The panels are sorted according to the anomaly rank in the dig list, with that rank indicated by a number in the top right corner of each panel. The anomaly number (or Target ID) is indicated in a box located in the bottom-left corner of each panel with an indication of the library fit metric. The closest library item is indicated just below. Actual TOI are highlighted in yellow; training items that are non-TOI are highlighted in light blue.

The first 11 items of the dig list were requested for training to learn about the site-specific TOI and environmental conditions and to assess the capability to recover reliable parameters: the first 3 items are 3 different types of 37 mm projectiles while the rest are metal scrap, soil or so-called hot-rocks. These were selected to search for a potentially smaller TOI, e.g. a fuze. For instance, the 5th item corresponds to an 81 mm tail boom that could resemble a 37 mm projectile.

The stage 1 list stopped at the 20th item on the list (highlighted in light blue), which coincides with the last TOI. The stop dig point on the fmal dig list is on the 26th item (red highlight). These last 6 items before the stopping point had similar decay rate but a smaller size than a small ISO. These were added as a safeguard against the risk of under-estimating the target size, which could occur if a strong background signal was not adequately compensated.

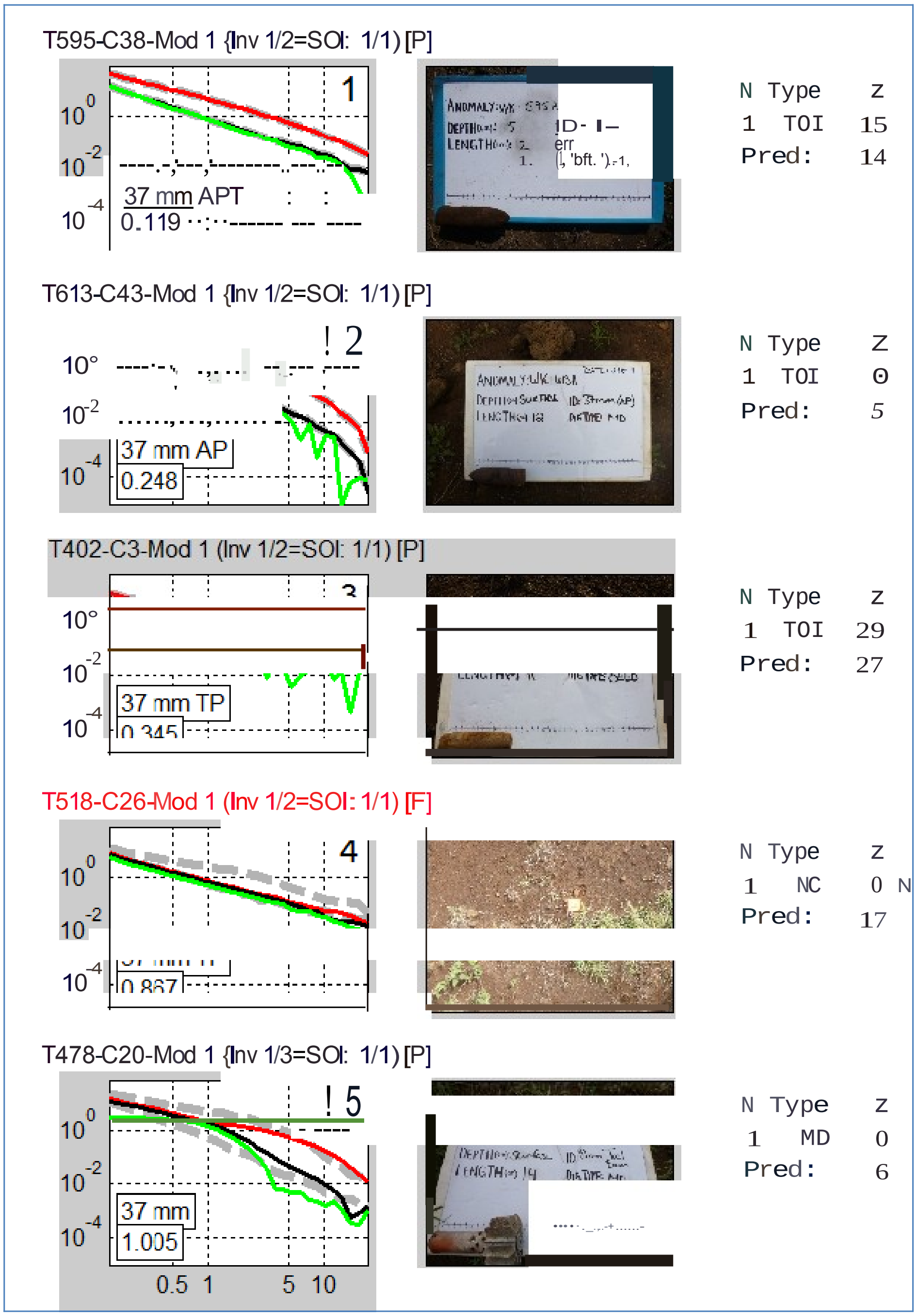


Figure 38: Ground truth for the first 5 training items.

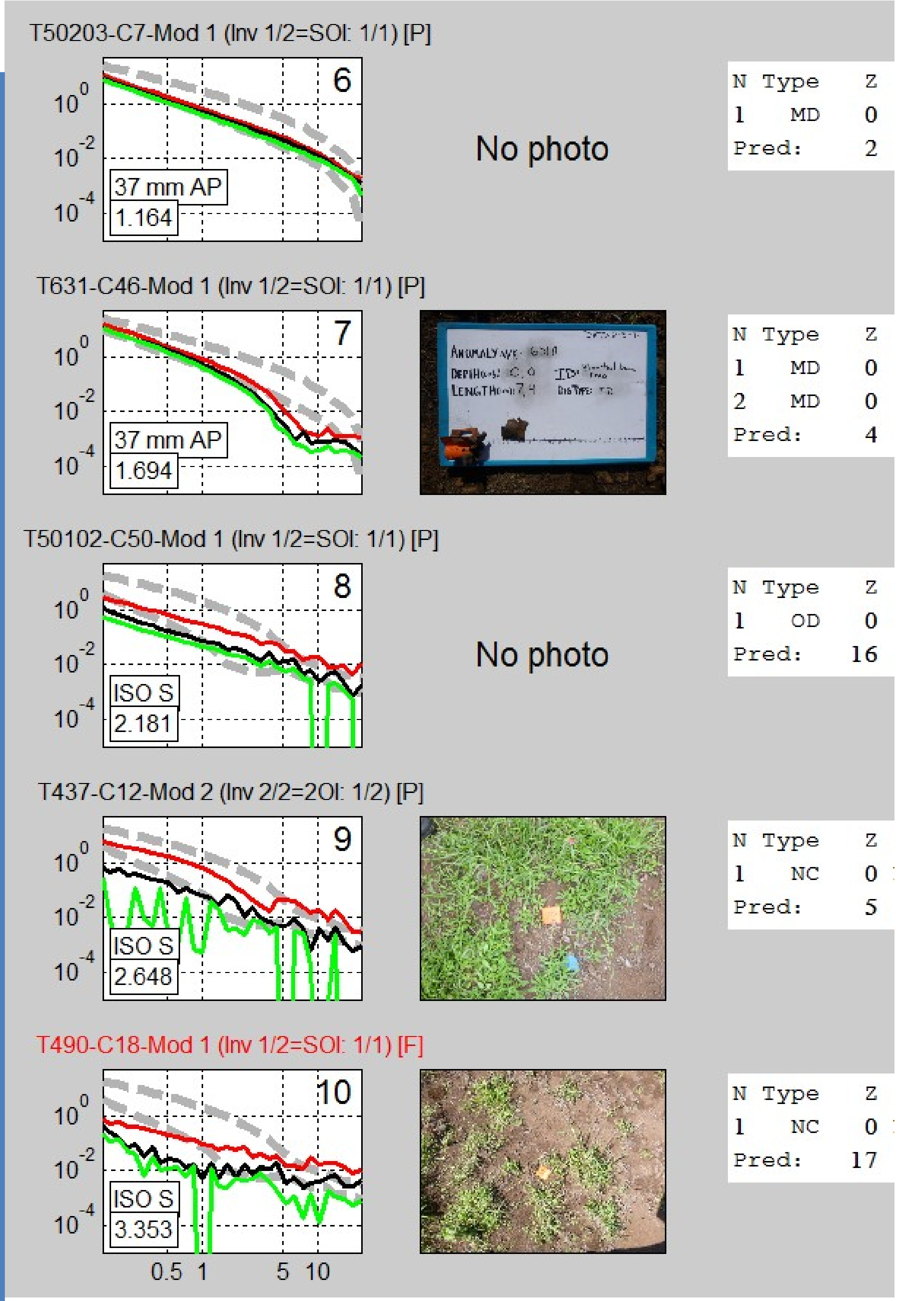
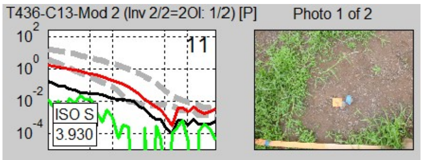


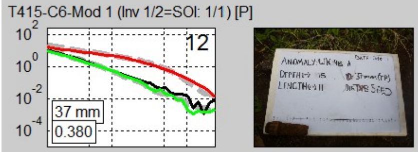
Figure 39: Ground truth for training items 6-10.

T436-C13-Mod 2 (Inv 2/2=2OI: 1/2) [P] Photo 1 of 2



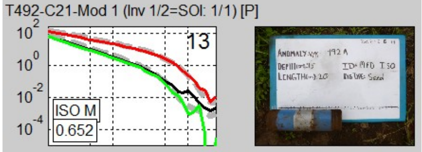
N Type Z
NC 0
Pred:

T415-C6-Mod 1 (Inv 1/2=SOI: 1/1) [P]



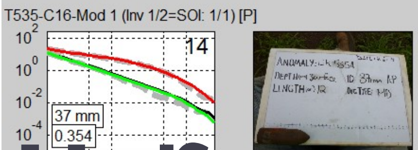
N Type Z
I TOI IS
Pred: 19

T492-C21-Mod 1 (Inv 1/2=SOI: 1/1) [P]

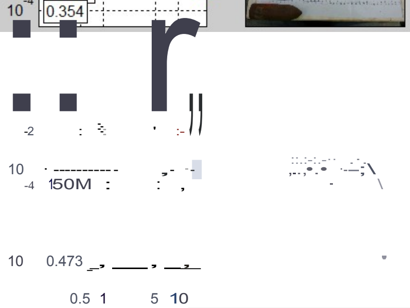


N Type Z
I TOI IS
Pred: 19

T535-C16-Mod 1 (Inv 1/2=SOI: 1/1) [P]



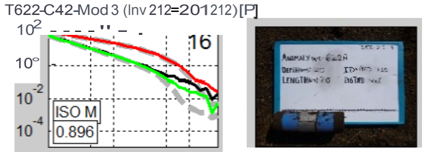
N Type Z
TOI 0
Pred: 2



Pred: 22

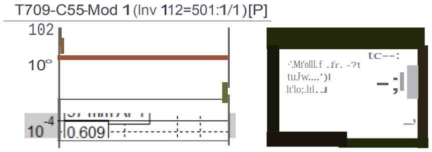
N Type Z
TOI 19

T622-C42-Mod 3 (Inv 212=201212) [P]



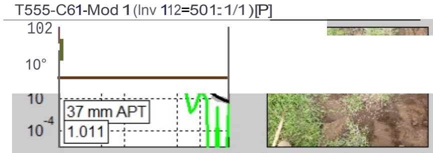
N ':'ype
O: 20
Pred.: 26

T709-C55-Mod 1 (Inv 112=501:1/1) [P]



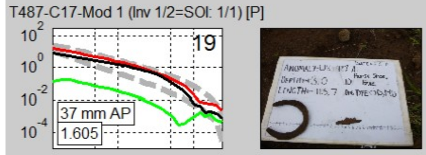
N ':'ype
':O: 21
?red: 27

T555-C61-Mod 1 (Inv 112=501:1/1) [P]



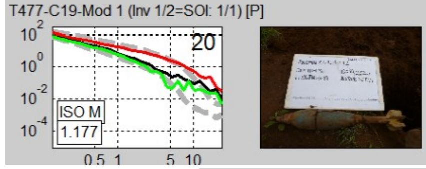
N Type
NC NaN 1\
Pred: 26

T487-C17-Mod 1 (Inv 1/2=SOI: 1/1) [P]



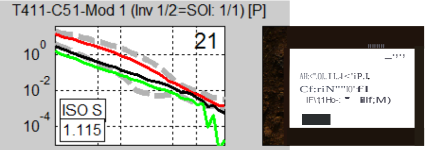
N Type
OD
2 MD 0
Pred: 9

T477-C19-Mod 1 (Inv 1/2=SOI: 1/1) [P]



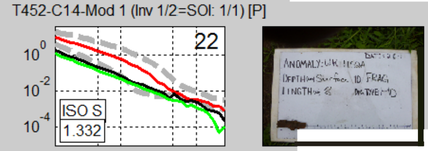
N ':'ype
O: 37
?red: 41

T411-C51-Mod 1 (Inv 1/2=SOI: 1/1) [P]



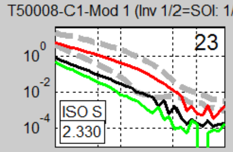
N Type
MD 0
Pred:

T452-C14-Mod 1 (Inv 1/2=SOI: 1/1) [P]



N Type
MD 0
Pred:

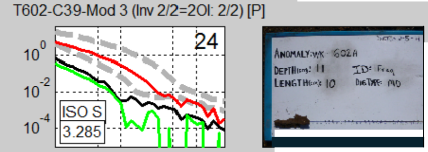
T50008-C1-Mod 1 (Inv 1/2=SOI: 1/1) [P]



No photo

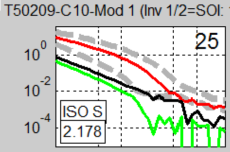
N Type
MD 0
Pred:

T602-C39-Mod 3 (Inv 2/2=2OI: 2/2) [P]



N Type
MD II
Pred:

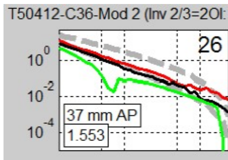
T50209-C10-Mod 1 (Inv 1/2=SOI: 1/1) [P]



No photo

N Type
MD 0
Pred:

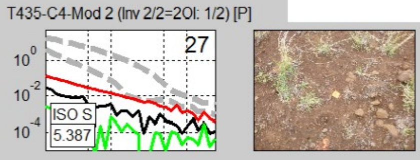
T50412-C36-Mod 2 (Inv 2/3=2OI: 1/2) [P]



No photo

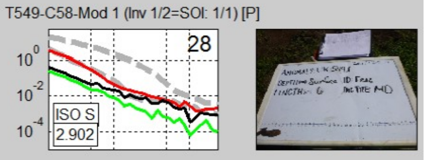
N Type
MD 0
Pred: 15

T435-C4-Mod 2 (Inv 2/2=2OI: 1/2) [P]



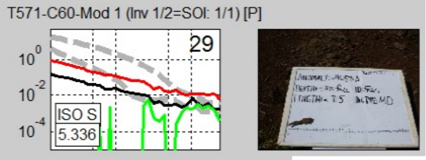
N Type
NC 0
Pred: 0

T549-C58-Mod 1 (Inv 1/2=SOI: 1/1) [P]



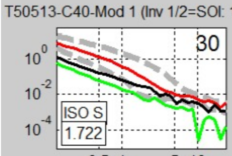
N Type
MD 0
Pred:

T571-C60-Mod 1 (Inv 1/2=SOI: 1/1) [P]



N Type
I MD 0
Pred: 17

T50513-C40-Mod 1 (Inv 1/2=SOI: 1/1) [P]



No photo

N Type
MD 0
Pred: 6